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Final

Phase III Aquifer Testing at Site 1 and Site 10 of Allegany Ballistics Laboratory Superfund Site

Rocket Center, West Virginia

Prepared for

Department of the Navy

Atlantic Division

Naval Facilities Engineering Command

Norfolk, Virginia

Contract No. N62470-95-D-6007
CTO-0116

January 2002

Prepared by

CH2MHILL

Baker
Environmental, Inc.

CDM
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Phase III Aquifer Testing at
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Contract Task Order - 0116
Contract Number N62470-95-D-6007
Navy CLEAN II Program

Prepared by

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January 2002

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Acronyms and Abbreviations

1,1-DCA	1,1-dichloroethane
1,2-DCA	1,2-dichloroethane
1,1-DCE	1,1-dichloroethene
1,2-DCE	1,2-dichloroethene
1,1,1-TCA	1,1,1-trichloroethane
ABL	Allegany Ballistics Laboratory
bgs	below ground surface
btoc	below top of casing
CLP	Contract Laboratory Program
CS	Confirmation Study
DNAPL	dense nonaqueous phase liquid
DO	dissolved oxygen
Eh	oxidation reduction potential
FFS	Focused Feasibility Study
ft^2/min	square feet per minute
EPA	U.S. Environmental Protection Agency
gpm	gallons per minute
IAS	Initial Assessment Study
ID	inside diameter
IRP	Installation Restoration Program
MC	methylene chloride
μmho/cm	micromhos per centimeter
μg/l	microgram per liter
μm	micrometer
mg/l	milligram per liter
msl	mean sea level
mV	millivolts
NACIP	Navy Assessment and Control of Installation Pollutants Program
NAVFAC	Naval Facilities Engineering Command, Atlantic Division
NAVSEA	Naval Sea Systems Command
NEESA	Navy Environmental Engineering Support Activity
NPL	National Priority List
NRC	National Research Council
OVM	organic vapor monitor
PCE	tetrachloroethene (perchloroethene)
ppb	parts per billion
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RI/FS	Remedial Investigation/Feasibility Study

Acronyms and Abbreviations (Continued)

TAL	Target Analyte List
TCE	trichloroethene
TCL	Target Compound List
TOC	total organic carbon
VC	vinyl chloride
VOC	volatile organic compound

1.0 Introduction

CH2M HILL was contracted by the Atlantic Division of the Naval Facilities Engineering Command (Navy) to perform Phase III Aquifer Testing at Site 1 and Site 10 of the Allegany Ballistics Laboratory Superfund Site (ABL) in Rocket Center, West Virginia. ABL is a government-owned (Navy), contractor-operated (Alliant Missile Product Company [AMPC]) research, development, testing, and production facility for solid propellant rocket motors. On May 31, 1994 ABL was added to the National Priority List (NPL).

Phase III Aquifer Testing activities occurred over a period of approximately 4 years from 1998 through 2001. The activities included installation of new monitoring wells and extraction wells, pump-testing wells both individually and in groups, and direct-push sampling of groundwater to better delineate areas of contamination. All of these activities were done for the purpose of improving and optimizing the groundwater extraction systems at sites 1 and 10.

Specific activities completed during Phase III Aquifer Testing were the following:

- A third alluvial extraction well (10EW37) was installed downgradient of the "hot spot" area, based on water-quality data collected from the Site 10 monitoring wells.
- Direct-push groundwater sampling was conducted at Site 10 to improve delineation of the leading edge of the contaminant plume in the alluvial aquifer. This was done to help determine the most appropriate location for a fourth alluvial extraction well (10EW38) to enable complete capture of the alluvial contaminant plume.
- To reduce uncertainty about the completeness of the hydraulic containment in the bedrock aquifer at the west end of Site 1, a new experimental extraction well was installed (1EW35) and tested and an existing bedrock monitoring well (1GW02) was modified and tested. The potential effectiveness of these experimental extraction wells was evaluated by performing yield tests.
- Several new monitoring wells were installed at Site 10 in both the alluvial and bedrock aquifers. Their purposes were to improve monitoring of vertical hydraulic gradients at Site 10, to improve delineation of the hydraulic capture zone produced by operation of the groundwater extraction system in the alluvial aquifer, and to assist in evaluating the hydraulic relationship between sites 1 and 10 (see following bullet).
- A large-scale bedrock pumping test was conducted using only the existing bedrock extraction wells at Site 1 as the pumping wells. This test had several purposes. One was to evaluate the effectiveness of bedrock extraction alone as a means of achieving hydraulic capture in both bedrock and alluvial aquifers at Site 1. Another was to evaluate the hydraulic influence of bedrock pumping at Site 1 on water levels and vertical gradients at Site 10. A third purpose was to acquire test data that would support the development and calibration of a unified groundwater flow model for both sites.

- Based on the results of the large-scale bedrock test, a three-dimensional groundwater flow model was developed and calibrated. It was then used to simulate the addition of bedrock extraction wells to the Site-10 groundwater extraction system.

The Phase III Aquifer Testing Report consists of seven sections and four appendices. Section 1 is an introduction to the Phase III testing activities and their objectives. Section 2 describes the site history and summarizes the previous investigations conducted at ABL. The various Phase III Aquifer Testing and related field activities are detailed in Section 3. The results of the second large-scale pumping test are presented and discussed in Section 4. Section 5 presents the unified groundwater flow model development and calibration, based on the results of the Phase III Aquifer Testing field activities. Section 6 documents the use of the groundwater model to simulate the addition of bedrock extraction wells to the Site-10 extraction system. Section 7 provides a list of the references utilized during preparation of this report.

The appendices included in this report are intended to provide detailed and supplemental information about activities that are summarized within individual sections of the report. Appendix A presets drilling and well installation details. Well construction logs are provided in Appendix B. Appendix C contains a memorandum detailing the yield testing activities and results for experimental extraction well 1EW35. Appendix D contains the hydrographs recorded by the data loggers during the large-scale bedrock aquifer test.

Because additional data have been collected since the *Focused Feasibility Study for Site 10 Groundwater at Allegany Ballistics Laboratory Superfund Site* (CH2M HILL, March 1998) was conducted, including the information presented in this report, it became necessary to revise the cost estimates for the various remedial alternatives developed during the Feasibility Study. Appendix E contains these revised detailed cost estimates, updated to include actual long-term monitoring and operation and maintenance costs and modified capital costs based on the optimal groundwater extraction-well configuration developed during this study.

2.0 Site Background

This section provides a brief description and history of ABL and the previous investigations conducted at the facility that focused on or included sites 1 and 10. Detailed background information on Site 1, Site 10, and the facility can be found in the Remedial Investigation Report (CH2M HILL, January 1996), Site 1 Focused Remedial Investigation Report (CH2M HILL, August 1995), Phase II Remedial Investigation Report (CH2M HILL, August 1996), Site 1 Groundwater Focused Feasibility Study Report (CH2M HILL, September 1996), Site 10 Groundwater Focused Feasibility Study Report (CH2M HILL, March 1998), Phase I Aquifer Testing Report (CH2M HILL, December 1998), Phase II Aquifer Testing at Site 1 Report (CH2M HILL, September 1999a), and Phase II Aquifer Testing at Site 10 Report (September 1999b).

2.1 Description and History

ABL is a government-owned (Navy), contractor-operated (AMPC) research, development, and production facility located in Mineral County, West Virginia. Since 1943, ABL has been used primarily for research, development, testing, and production of solid propellants and motors for ammunition, rockets, and armaments. The facility consists of two plants (Figures 2-1). Plant 1, occupying approximately 1,572 acres, is owned by the Navy and operated by AMPC. Plant 2, a 56-acre area adjacent to Plant 1, is owned exclusively by AMPC. Most of Plant 1 is in the floodplain of the North Branch Potomac River, with the remaining acreage on forested mountainous land. Figure 2-2 shows that Site 1 is located along the northern perimeter of Plant 1, adjacent to the North Branch Potomac River. Figure 2-2 also shows that Site 10 is located in the south-central portion of Plant 1, in the vicinity of former production wells A and C (i.e., PWA and PWC).

2.2 Summary of Previous Investigations

A number of investigations have been conducted at ABL for the purpose of identifying and evaluating areas where hazardous materials currently exist or existed in the past. In 1982, an Initial Assessment Study (IAS) was conducted during which seven sites were recommended for further evaluation of potential impacts on human health and the environment by suspected contaminants at the site. At that time, Site 1 was defined as the Northern Riverside Waste Disposal Area. Between June 1984 and August 1987, a Confirmation Study (CS) was conducted at ABL which recommended further investigations for a number of sites, including Site 1 and Site 10. The CS identified Site 10 as Site PWA, because contamination was detected in PWA and PWC during this investigation, but the source was not identified. In order to be consistent with other numbered IRP sites at ABL, the site was renamed Site 10 in 1995 and now includes the area around Building 157 as well as PWA and PWC.. From 1959 until the early 1960s, a trichloroethene (TCE) still operated just outside Building 157, and releases from these activities are believed to be the source of volatile organic compound (VOC) contamination detected in PWA and PWC.

In 1992, CH2M HILL was contracted by the former operator of ABL (Hercules Aerospace Company) to conduct a remedial investigation (RI) of a number of sites, including Site 1 and Site 10. Activities conducted by CH2M HILL during the RI included a focused facility audit to determine possible source(s) of VOC contamination at Site 1 and Site 10. Well installation, soil and groundwater sampling, and well testing also were conducted at Site 1 and Site 10 during the RI.

The RI Report (CH2M HILL, January 1996), which documented the 1992 RI, recommended a focused investigation of the North Branch Potomac River along Site 1 to determine the hydraulic relationship between the river and the alluvial and bedrock aquifers at Site 1 and to evaluate the nature and extent of contamination in the reach of the river along the site. The RI Report also recommended an additional investigation at Site 10 to better define the nature and extent of contamination and to support human health and environmental risk assessments.

In 1994, CH2M HILL was contracted by the Navy to conduct a Focused RI at Site 1. The Focused RI further defined the nature and extent of soil and groundwater contamination at Site 1 and surface-water and sediment contamination in the North Branch Potomac River adjacent to Site 1 (CH2M HILL, August 1995). The Focused RI also provided water-quality and hydraulic data for groundwater in the bedrock aquifer across the river north of Site 1.

Based on the results of the Site 1 Focused RI and previous investigations, a Focused Feasibility Study (FFS) for groundwater was conducted in 1995 to evaluate various remedial alternatives for preventing further off-site migration of contaminated groundwater at Site 1. The Site 1 FFS suggested groundwater extraction at the site as the most viable remedial option for achieving the objective of hydraulic containment (CH2M HILL, September 1996).

In 1994, CH2M HILL was contracted by the Navy to conduct a Phase II RI at Site 10, which further defined the nature of soil contamination in the vicinity of the former TCE still. Based on the results of the Phase II RI and previous investigations, an FFS was conducted in 1998 for Site 10 groundwater to evaluate potential remedial alternatives for addressing groundwater contamination at the site. The Site 10 FFS suggested groundwater extraction as the most viable remedial option.

2.2.1 Previous Aquifer Testing at Site 1

Phase I Aquifer Testing was conducted between March and May 1996 to refine the existing understanding of the hydraulic properties and interrelationship of the alluvial and bedrock aquifers at site 1. This testing was completed to better assess the feasibility of groundwater extraction to provide hydraulic containment of contaminated alluvial and bedrock groundwater at Site 1 and to prevent its discharge to the North Branch Potomac River. For Phase I Aquifer Testing, two clusters of aquifer test and observation wells were installed at Site 1, one at each end of the active Burning Ground (Figure 2-3). As shown in Figure 2-3, each cluster consisted of four bedrock wells and two alluvial wells. For each long-term bedrock-aquifer test, the bedrock test well was pumped at a constant rate while the water levels in the remaining three bedrock wells were monitored. Similarly, for each long-term alluvial-aquifer test, the alluvial well adjacent to the bedrock test well was pumped at a constant rate while the water level in the alluvial observation well was monitored.

The results of aquifer testing, documented in the Phase I Aquifer Testing Report (CH2M HILL, December 1998), were used to develop generic groundwater-flow models which, in turn, were used to aid in the design of the groundwater extraction-well configuration proposed for the site.

Phase II Aquifer Testing was completed at Site 1 between September and December 1996. The first objective of the Phase II Aquifer Testing was to install the extraction and monitoring-well network proposed in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). The second objective was to confirm the assumptions made in the Phase I Aquifer Testing Report concerning the hydraulic characteristics of the alluvium and bedrock at Site 1, on which the groundwater models developed for the site were based. It was these groundwater models that were used to develop the extraction-well configuration installed during Phase II Aquifer Testing. The final objective was to evaluate the newly installed extraction wells for their production capacity and constituent concentrations. To satisfy these objectives, Phase II Aquifer Testing activities at Site 1 included drilling and well installation, geophysical logging of all newly installed bedrock wells, aquifer testing, water-level measuring, and groundwater sampling. These activities are documented in the Phase II Aquifer Testing at Site 1 Report (CH2M HILL, September 1999a). Figure 2-4 shows the configuration of the extraction and monitoring well network that was installed during the Phase II aquifer test, as well as other wells that had been installed previously at the site. The conclusions of the Phase II Aquifer Testing at Site 1 are summarized below.

The interpreted piezometric surfaces of the alluvial and bedrock aquifers at Site 1 were refined based on the results of Phase II Aquifer Testing. Additional water-level data indicated that west of the Burning Ground in both aquifers, groundwater flow was to the north-northwest rather than the north-northeast. The water-level data also suggested the hydraulic gradient increased from approximately 0.01 in the central and eastern portion of the site to about 0.03 near the western end of the Burning Ground.

Interpretation of the results of yield testing conducted on every third alluvial extraction well installed during Phase II Aquifer Testing indicated that the alluvial aquifer in the west-central part of Site 1 has a lower transmissivity than was assumed in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). Consequently, the well spacings in this area were reduced by adding two alluvial extraction wells to the configuration. In addition, yield testing on all alluvial extraction wells installed during Phase II Aquifer Testing required that the flow rates in several of the extraction wells in the west-central area be reduced from the assumptions in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). All other aquifer testing activities confirmed that extraction well flow rates assumed in the models used to develop the extraction well configuration in the Phase I Aquifer Testing Report were attainable. In addition, the constant-rate tests indicated sufficient hydraulic connection between bedrock extraction wells to attain containment in the bedrock aquifer.

During the Phase II Aquifer Test, treatment plant influent concentrations were estimated using the analytical results and extraction flow rates of the Site 1 extraction wells installed. These calculations were used in the design of the groundwater treatment processes for the treatment plant.

2.2.2 Previous Aquifer Testing at Site 10

Phase I Aquifer Testing at Site 10 was conducted between March and May 1996. There were three primary objectives to the Phase I Aquifer Testing: 1) to better assess the feasibility of groundwater extraction to capture the alluvial and bedrock contaminant plumes at Site 10; 2) to define the extent of groundwater VOC contamination; and 3) to refine the existing understanding of the hydraulic properties and interrelationship of the alluvial and bedrock aquifers at the site.

For Phase I Aquifer Testing, the results of a direct-push investigation at and around Site 10 were used to better define the extent of VOC contamination in the alluvial aquifer and to select the location of an alluvial aquifer test well. The location selected corresponded to the area where the highest VOC concentrations were detected during direct-push sampling. The purpose of testing this area was to assess the feasibility of groundwater extraction in removing the most concentrated portion of the contaminant plume (i.e., hot spot). A bedrock aquifer test well was installed adjacent to the former TCE still location under the assumption that the highest bedrock VOC concentrations would likely be directly below the former TCE still as a result of vertical contaminant migration. The locations of the Phase I Aquifer Test wells, as well as other wells at and around Site 10, are shown in Figure 2-5. For the long-term bedrock-aquifer test, the bedrock test well (i.e., 10GW01) was pumped at a constant rate while the water levels in other Site 10 bedrock wells, as well as alluvial wells, were monitored. Similarly, for the long-term alluvial-aquifer test, the alluvial test well (i.e., 10GW11) was pumped at a constant rate while the water levels in the adjacent alluvial and bedrock observation wells were monitored.

The results of aquifer testing, documented in the Phase I Aquifer Testing Report (CH2M HILL, December 1998), were used to develop a generic groundwater-flow model which, in turn, was used to aid in the design of the groundwater extraction-well configuration proposed for the site.

Phase II Aquifer Testing was conducted at Site 10 between September and December 1996. The first objective of Phase II Aquifer Testing at Site 10 was to install the extraction and monitoring-well network proposed in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). The second objective was to confirm the assumptions made concerning the hydraulic characteristics of the alluvium in the Phase I Aquifer Testing Report, on which the alluvial groundwater model developed for Site 10 was based. It was this groundwater model that was used to develop the extraction-well configuration believed necessary to capture the VOC contaminant plume originating at the former TCE still. The final objective was to evaluate the newly installed extraction wells for their production capacity and constituent concentrations through testing and sampling. To satisfy these objectives, Phase II Aquifer Testing activities at Site 10 included drilling and well installation, geophysical logging of all newly installed bedrock wells, aquifer testing, water-level measuring, and groundwater sampling. These activities are documented in the Phase II Aquifer Testing at Site 10 Report (CH2M HILL, September 1999b).

The groundwater modeling results, based on the Phase I Aquifer Testing results, indicated that groundwater capture could be attained with a group of five alluvial extraction wells, one approximately 250 feet downgradient of the contaminant plume "hot spot" and a linear alignment of four additional alluvial extraction wells another 500 feet downgradient. Figure

2-6 shows four of these five extraction wells (i.e., 10EW01 and 10EW3 through 10EW05). During installation of the linear alignment of extraction wells from south to north, drilling observations suggested that the hydrogeologic characteristics were unfavorable for groundwater extraction and substantially dissimilar to the characteristics observed at the test well location (i.e., 10GW11) and used in the groundwater flow model. Therefore, only the southern three of the four proposed extraction wells of the linear alignment (i.e., 10EW03, 10EW04, and 10EW05) and one of the six intended monitoring wells (i.e., 10GW13) were installed. Proposed extraction well 10EW02 was not installed at the northern end of the linear alignment.

In addition to the assumption that the alluvial aquifer contaminant plume could be captured by the aforementioned extraction-well configuration, it was also assumed that this configuration could capture the bedrock contaminant plume. This assumption was based on the fact that the bedrock contaminant plume was much smaller than the alluvial contaminant plume, that the "footprint" of the bedrock plume was contained within the "footprint" of the alluvial plume, and that the vertical hydraulic gradients measured at Site 10 historically had been neutral or upward. Therefore, in theory, groundwater extraction from the alluvial aquifer should have produced or enhanced upward flow from the bedrock aquifer, thereby allowing the alluvial extraction wells to capture the bedrock contamination.

After performing aquifer testing on all newly installed extraction wells and verifying that the three eastern-most extraction wells had low productivities, four additional alluvial monitoring wells were installed around the perimeter of Site 10 in a second phase of drilling. These wells were intended to assist in better evaluating the hydraulic and chemical properties of the alluvial aquifer in the eastern portion of site 10. Because of the low productivity of wells 10EW03, 10EW04, and 10EW05, they were never put into service as extraction wells.

Information obtained during Phase II Aquifer Testing refined the interpretation of the physical and chemical properties of the alluvial and bedrock aquifers at and adjacent to Site 10. Primarily, as indicated above, it was determined that the highly transmissive material of the alluvial aquifer in the vicinity of the test well does not persist eastward across the site. Further, the most concentrated portion of the alluvial-aquifer VOC contaminant plume was found to be primarily within the area containing the highly transmissive sediment, possibly confined by bedrock topographic highs to the north and south of Site 10. Although localized variations exist in the piezometric surface of the alluvial aquifer at Site 10, the overall direction of groundwater flow, and contaminant migration, is east-northeast across the site.

Another significant finding of Phase II Aquifer Testing was that the bedrock in the eastern portion of Site 10 was less fractured and less transmissive than the bedrock in the western portion. Chemical data collected from the bedrock wells during Phase II Aquifer Testing suggested the VOC contaminant plume had not moved far from the former TCE still and that its movement is likely along preferential fractures or bedding planes.

Finally, testing of all newly installed alluvial extraction wells suggested groundwater extraction from the linear alignment east of Site 10 would not result in capture of the VOC contaminant plume as simulated in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). However, the testing indicated that groundwater extraction from well

10EW01 (since renamed 10EW35) was viable and would provide capture of a portion of the most concentrated area of the plume. Because groundwater data collected during Phase II Aquifer Testing suggested well 10GW11 was installed in the vicinity of the most highly contaminated portion of the alluvial aquifer, the well was modified so that it could be used as an extraction well and was re-named 10EW36.

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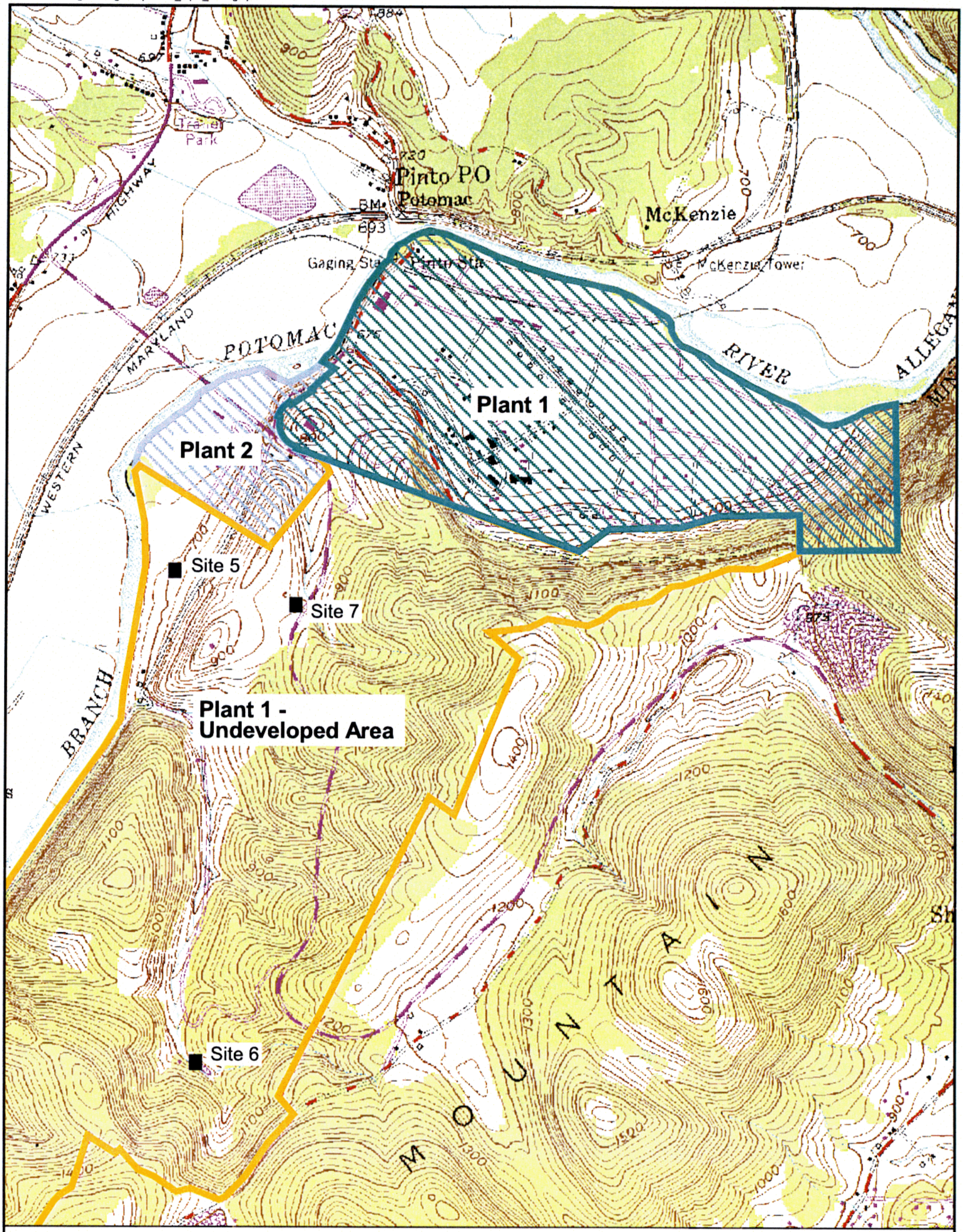

LEGEND
- Plant 1
- Plant 2
- Plant 1 - Undeveloped Area

N

200 0 200 400 Feet

Figure 2-1
Location Map
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Source: USGS 7.5 minute Cresaptown, WV-MD quadrangle map.

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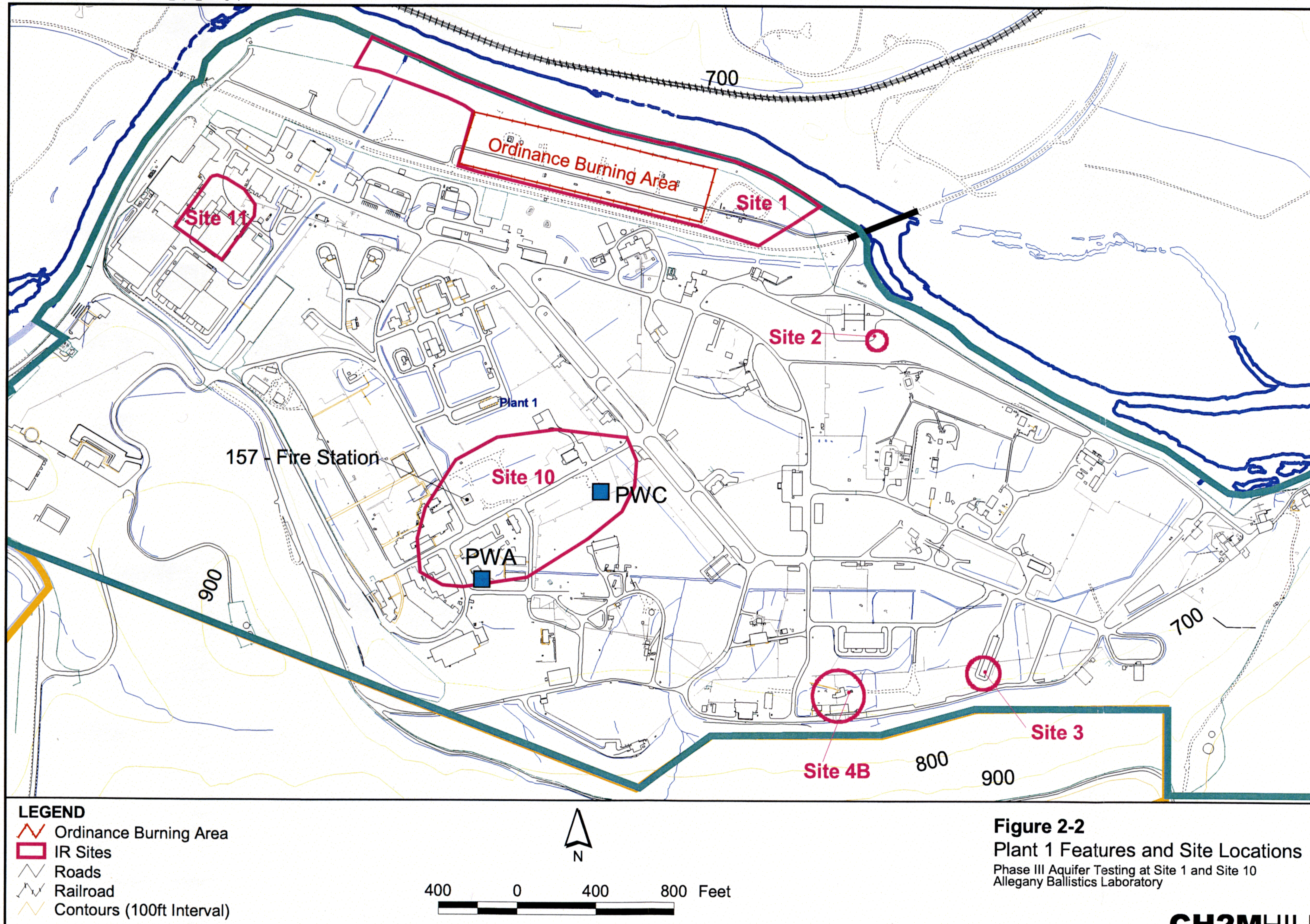

Figure 2-2
Plant 1 Features and Site Locations
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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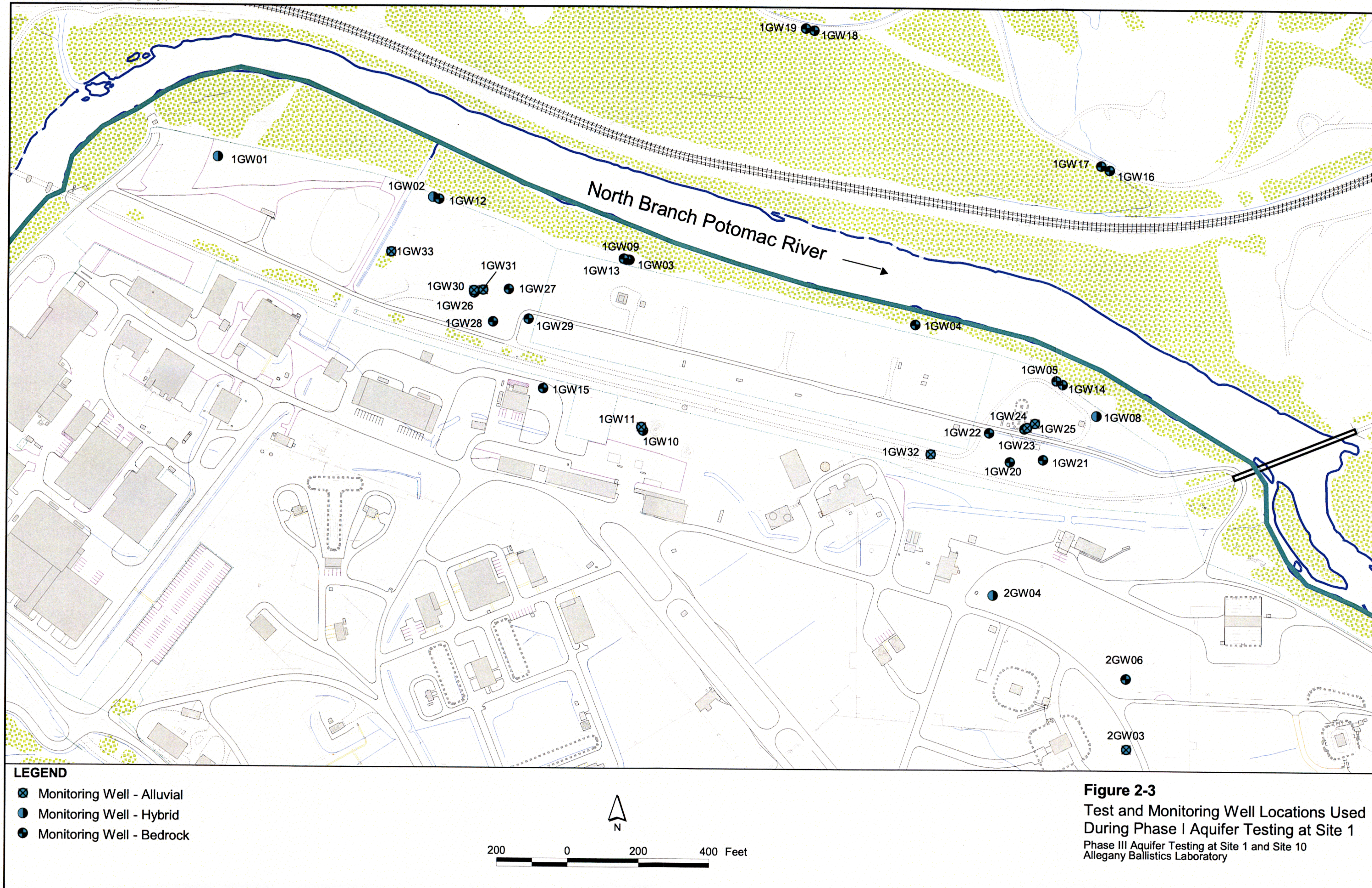

Figure 2-3
Test and Monitoring Well Locations Used During Phase I Aquifer Testing at Site 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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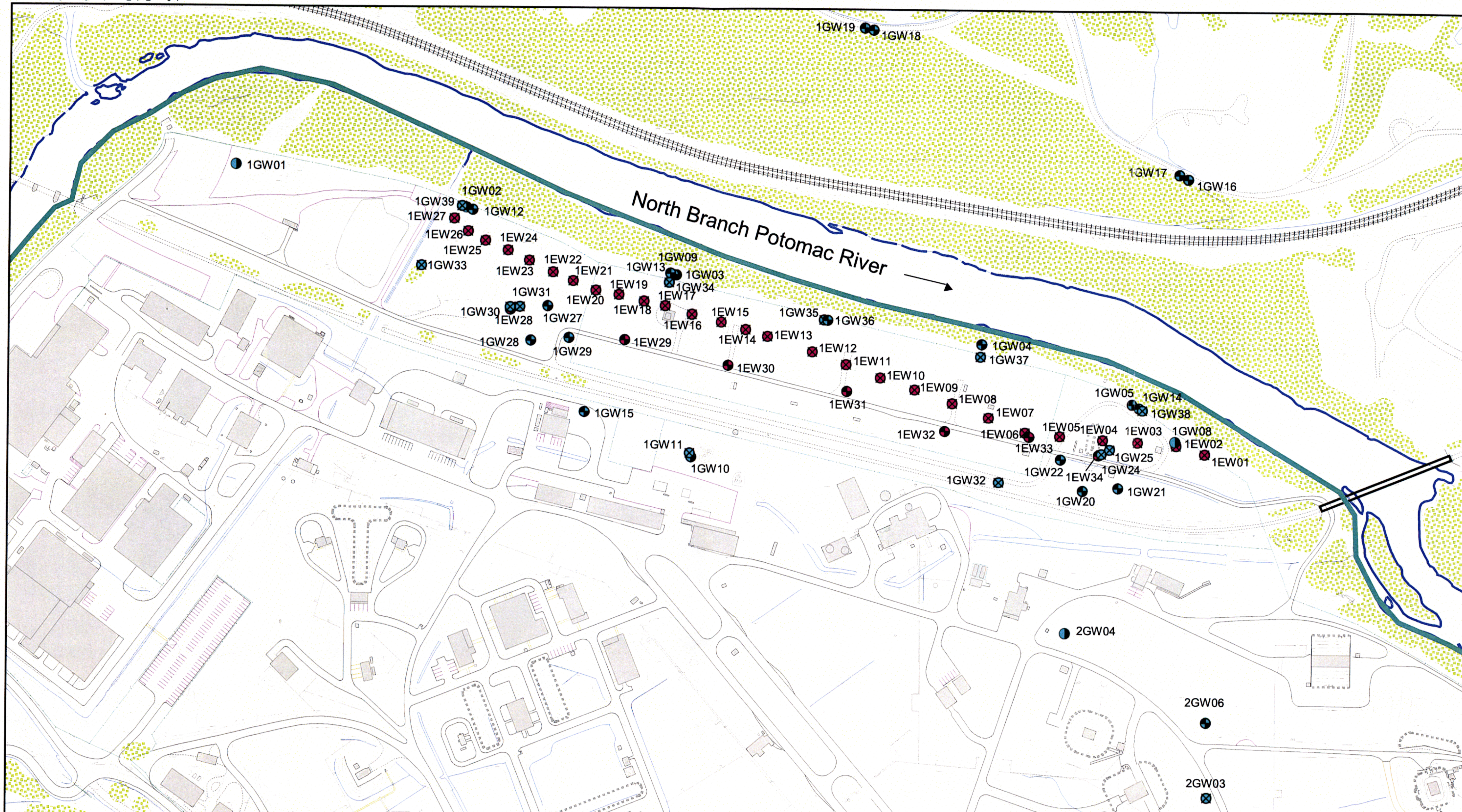

LEGEND

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Alluvial
- Monitoring Well - Hybrid
- Monitoring Well - Bedrock

Figure 2-4
Extraction and Monitoring Well Locations Used During Phase II Aquifer Testing at Site 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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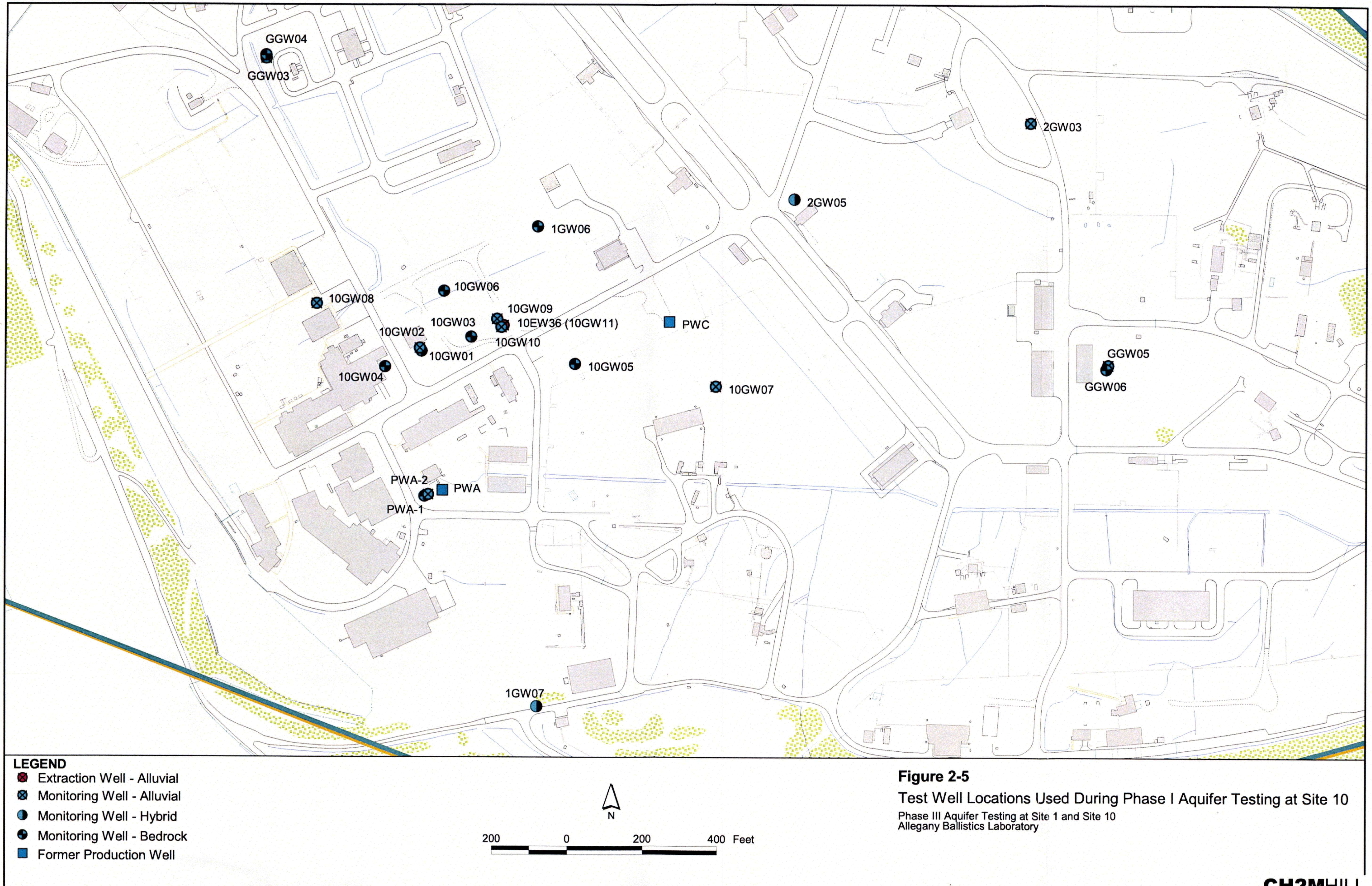

Figure 2-5

Test Well Locations Used During Phase I Aquifer Testing at Site 10

Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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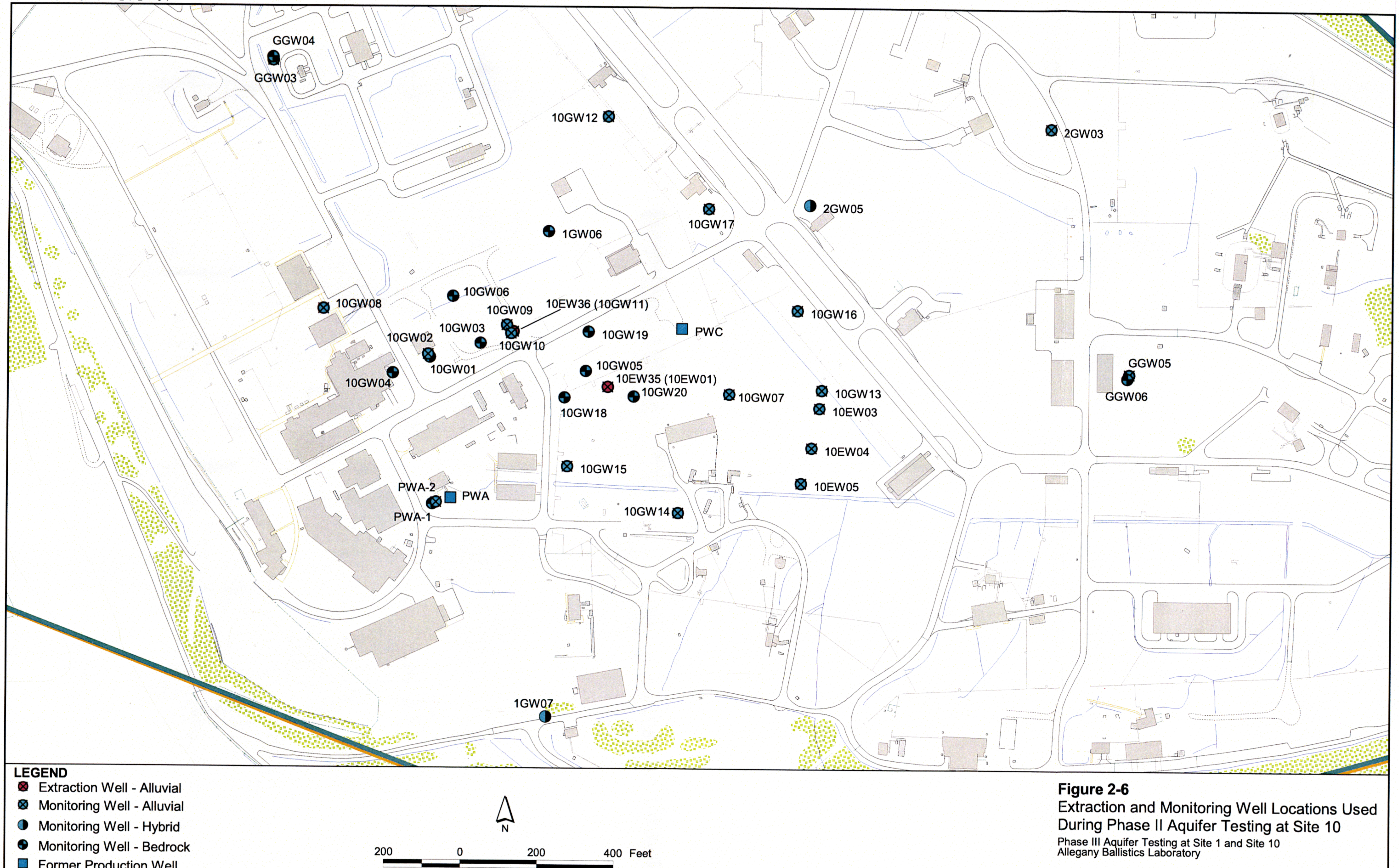

LEGEND

- Extraction Well - Alluvial
- Monitoring Well - Alluvial
- Monitoring Well - Hybrid
- Monitoring Well - Bedrock
- Former Production Well

Figure 2-6
Extraction and Monitoring Well Locations Used During Phase II Aquifer Testing at Site 10
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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3.0 Phase III Aquifer Testing Activities

This section documents the field activities that occurred at ABL during Phase III Aquifer Testing between June 1998 and July 2001, with special emphasis on the large-scale bedrock test that occurred between June 25 and July 10, 2001. To assist with understanding all of the various Phase III Aquifer Testing activities, a chronological summary of the activities is provided in Table 3-1. General descriptions of wells installed during Phase III Aquifer Testing are provided in Table 3-2. The facility monitoring well and extraction well construction detail tables from the Phase II Aquifer Testing reports also have been updated with the additional wells installed during Phase III Aquifer Testing and are presented as tables 3-3 (monitoring wells) and 3-4 (extraction wells).

As discussed in Section 1.0, the objectives of the Phase III Aquifer Testing activities were varied, from installing additional extraction wells in an effort to attain more complete hydraulic containment to conducting a large-scale bedrock test to evaluate the hydraulic relationship between Site 1 and Site 10. To satisfy these objectives, Phase III Aquifer Testing activities at Site 1 and Site 10 included direct-push groundwater sampling, drilling and well installation, aquifer testing, and water-level measuring. The details of each activity are discussed below.

3.1 Installation of Third Alluvial Extraction Well at Site 10

Subsequent to Phase II Aquifer Testing, it was determined that hydraulic containment of the VOC contaminant plume in the alluvial aquifer might be enhanced by the installation of an additional alluvial extraction well. This assumption was based on the belief that migration of the alluvial VOC plume was being channeled in a northeast direction within a bedrock "trough" between wells 10GW13 and 10GW17. Therefore, a plan was developed to install an additional extraction well (to enhance contaminant plume capture) and a series of monitoring wells (to enhance evaluation of hydraulic containment and vertical hydraulic gradients). The Memorandum *Installation of Extraction and Monitoring Wells at Site 10* (CH2M HILL, July 22, 1998) describes the rationale and approach for installing this extraction well and several additional monitoring wells (i.e., 10GW21 through 10GW24).

In July 1998, an additional alluvial extraction well (i.e., 10EW02) was installed about 90 feet north of 10GW07, as described in the aforementioned memorandum. However, yield testing determined that this well was unable to produce a sufficient quantity of water (i.e., less than 2 gpm). During its yield test, 10EW02 was sampled and analyzed for VOCs using USEPA Method 624 at the AMPC laboratory. The only detected constituent in 10EW02 was TCE, at a concentration of 28 $\mu g/l$. Because of its low yield, the Partnering Team decided to abandoned 10EW02 and determine the suitability of the alluvial aquifer around well 10GW07 for alluvial groundwater extraction because this well had historically contained 120 $\mu g/l$ of TCE. To do this, a yield test was performed on well 10GW07 and the well found to be capable of producing 5 gpm.

Based on the results of the 10GW07 yield test, another alluvial extraction well was installed adjacent to well 10GW07 and designated 10EW06 to avoid confusion with the recently installed and abandoned 10EW02. Well 10EW06 was yield tested and found to be capable of producing approximately 2.6 gpm. During its yield test, well 10EW06 was sampled and analyzed for VOCs using USEPA Method 624 at the AMPC laboratory. The only detected constituent in well 10EW06 was TCE, at a concentration of 22 μg/l. To maintain consistency with other extraction wells, well 10EW06 has since been re-named 10EW37. Figure 3-1 shows the location of well 10EW37 and monitoring wells 10GW21 through 10GW24. Appendix A discusses the specific well installation activities and Appendix B contains copies of the well construction diagrams.

3.2 Installation of Fourth Alluvial Extraction Well at Site 10

Once the three alluvial extraction wells at Site 10 were put into operation in February 1999, it soon became apparent that they were capturing not only the "hot spot" area, but were also capturing all but the very northeastern tip of the alluvial aquifer contaminant plume. Therefore, in order to better delineate the northeastern extent (i.e., downgradient-most) of the alluvial aquifer plume and select the most appropriate location for a fourth alluvial extraction well to capture this area, a direct-push investigation was performed on June 6 and June 7, 2000. The results of this investigation were documented in the Draft Technical Memorandum *Soil and Groundwater Sampling and Well Installation Activities at Site 4B and Site 10 at Allegany Ballistics Laboratory* (CH2M HILL, January 15, 2000).

For the direct-push investigation, 10 groundwater samples were collected along three northwest-southeast transects in the vicinity of the suspected northeastern tip of the TCE plume at Site 10 (Figure 3-2). At each direct-push location shown in Figure 3-2, screening-level groundwater samples were collected using a peristaltic pump fitted with Teflon tubing. The groundwater samples were analyzed by the onsite AMPC laboratory, for VOCs using USEPA Method 624.

Only two VOCs, toluene and TCE, were detected in any of the direct-push groundwater samples and neither was detected above its USEPA maximum contaminant level (MCL). Of the 10 samples collected, only 3 samples (i.e., AS10-DP02, AS10-DP08, and AS10-DP10) contained VOCs at or above laboratory detection limits. TCE was detected in only groundwater sample AS10-DP02 at a concentration of 3.6 μg/l, which is below the 5 μg/l MCL. Toluene was detected in groundwater samples AS10-DP08 and AS10-DP10 at concentrations of 6 μg/l and 2 μg/l, respectively, both of which are below the MCL of 1,000 μg/l. Figure 3-2 presents the direct-push TCE analytical results and depicts the approximate northeastern boundary of the TCE plume in alluvial groundwater, based on the direct-push results.

As noted above, the results of the direct-push groundwater sampling activity were used to determine the most appropriate location for an alluvial extraction well. Therefore, in July 2000, extraction well 10EW38 was installed, as was monitoring well 10GW25 for use in conjunction with monitoring well 10GW16 to verify hydraulic containment at the downgradient edge of the alluvial aquifer contaminant plume. Figure 3-2 shows the locations of both of these wells. Appendix A discusses the specific well installation activities and Appendix B contains copies of the well construction diagrams.

3.3 Installation and Testing of Experimental Extraction Well 1EW35 at Site 1

Since the groundwater extraction system at Site 1 became operational in September 1998, monthly water-level monitoring has shown that the groundwater elevation in the western-most bedrock monitoring well (i.e., 1GW12) has been above the water level in the adjacent North Branch Potomac River during most of the measurement events. Therefore, in an initial effort to reduce the water level in this well and provide a higher level of assurance of containment in the bedrock at the western end of Site 1, an experimental bedrock extraction well (i.e., 1EW35) was installed and tested adjacent to alluvial extraction well 1EW26 (Figure 3-3).

As shown in Table 3-2, the well was installed in July 2000 and has an effective screen interval (i.e., open borehole) of 38.5 to 65 feet below ground surface (bgs). This well was installed only to 65 feet bgs (as opposed to the more standard 90 feet bgs of the other bedrock extraction wells at Site 1) because a significant water-bearing fracture was identified between 58 and 59 feet bgs. Appendix A presents the details of well installation and the well construction diagram for well 1EW35 is presented in Appendix B.

On August 3, 2000, a yield test was conducted on well 1EW35 to determine whether pumping the well could provide the hydraulic containment desired at the west end of Site 1, as measured by a response in well 1GW12. A detailed discussion of the yield test and its results are documented in the Memorandum *Yield Test of Well 1EW35 at Allegany Ballistics Laboratory, Site 1* (CH2M HILL, August 22, 2000), which is presented in Appendix C. To summarize, the yield test results suggest well 1EW35 can be pumped at high rates (greater than about 66 gpm) without causing enough drawdown in well 1GW12 to show sufficient hydraulic containment of bedrock groundwater at the west end of Site 1. Well 1EW35 apparently has a fairly direct connection to the North Branch Potomac River through major bedrock fractures and can therefore sustain very high pumping rates without significant affect on the bedrock piezometric surface. In fact, it is estimated that over 25 percent of the groundwater treatment plant's maximum capacity would be necessary to include this well in the extraction-well network and even then it may not produce sufficient drawdown in the west end monitoring wells.

3.4 Testing and Modification of Monitoring Well 1GW02 at Site 1

Because experimental extraction well 1EW35 was not believed to be a viable option for bedrock groundwater extraction at the west end of Site 1, the focus was shifted to testing wells 1GW02 and 1GW12 (believed to be adjacent bedrock wells) to evaluate their hydraulic interconnection and evaluate the possibility of well 1GW02 pumping to exert hydraulic influence over well 1GW12. The locations of these wells are shown in Figure 3-3.

Well 1GW02 was installed in June 1984 during Confirmation Study (Interim RI). The well construction log indicated that this well was installed with a 6-inch-diameter surface casing that extended into bedrock (29 feet bgs) and a 6-inch-diameter borehole that extended to 40 feet bgs. The construction log also indicated that well 1GW02 was constructed with a 2-

inch-diameter PVC solid casing from 0 to 10 feet bgs and a 2-inch-diameter PVC screen from 10 to 40 feet bgs. Similarly, well 1GW12 was surface-cased to about 33 feet and constructed of 2-inch-diameter PVC well casing and screen, but was screened from 70 to 80 feet bgs.

Based on the assumptions above, a simple test was conducted in February 2001 to evaluate the hydraulic connection between these two wells. First, well 1GW12 was pumped while the water level in well 1GW02 was automatically recorded using a transducer and datalogger. The results of this first test showed that well 1GW12 could not sustain a flow rate of even 1 gpm and that the brief pumping did not produce a detectable change in the water level of well 1GW02. Next, the pump and transducer/datalogger were switched and well 1GW02 was pumped at a sustainable rate of 3 gpm, which produced about 10 feet of drawdown in well 1GW12.

Based on these results, the ABL Partnering Team decided to convert 1GW02 into a bedrock extraction well (i.e., make it a 6-inch-diameter well like the other extraction wells). In March 2001, the modification of 1GW02 began by removing the existing PVC casing and screen and reaming the borehole. Almost immediately upon the start of reaming, it was discovered that the surface casing only extended to about 3 feet bgs and that the well, therefore, was a hybrid well, screened across the alluvium/bedrock contact (i.e., 10 to 40 feet bgs). Therefore, in order to convert this well to standard bedrock well construction, a surface casing was installed to 37 feet bgs (i.e. about 3 feet into competent bedrock) before drilling in the bedrock proceeded. Once the grout around the surface casing set up, the borehole was reamed in approximately 5-foot intervals until a final depth of 80 feet was attained. After each 5-foot interval was reamed, the well was pumped to measure the hydraulic response in well 1GW12, with the intent to stop drilling if the desired hydraulic response was observed. Between 40 and 80 feet bgs, little or no hydraulic response was measured in well 1GW12 during each pumping of well 1GW02. Based on this information, it is now assumed that the hydraulic response measured in well 1GW12 when well 1GW02 was first pumped in February 2001 was propagated through the alluvial screened interval, which was sealed off when the surface casing was installed during its modification.

In addition to the conclusion drawn above, it is now believed that well 1GW12 is not well-connected with the surrounding bedrock and, therefore, likely does not accurately represent bedrock water-level conditions at the west end of Site 1 and its removal from the water-level monitoring program should be considered.

Appendix A discusses the specific well modification activities at well 1GW02 and Appendix B contains a copy of the well construction diagram.

3.5 Aquifer Testing

There were several objectives to performing the large-scale aquifer tests at sites 1 and 10. As noted in Section 1.0, the main objectives were to: (1) determine if bedrock pumping along could achieve hydraulic containment in both the alluvial and bedrock aquifers at Site 1 and (2) evaluate the degree of hydraulic interconnection between the aquifers at sites 1 and 10. Both the initial aborted and second successful large-scale tests are described below. The results of the successful large-scale test are summarized and discussed in Section 4.0.

3.5.1 Initial Large-Scale Bedrock Aquifer Test

As noted above, one of the objectives of the large-scale test was to evaluate the hydraulic interconnection between sites 1 and 10. To assist in this evaluation, two additional bedrock monitoring wells were installed in areas between Site 1 and Site 10 prior to conducting the test. Monitoring well 10GW26 was installed adjacent to existing alluvial well 10GW12 and monitoring well 10GW27 was installed adjacent to the existing hybrid well 2GW05. These wells were also used to evaluate the vertical hydraulic gradient between the alluvial and bedrock aquifers in those areas. Construction details for wells 10GW26 and 10GW27 are presented in tables 3-2 and 3-3. Appendix A discusses the specific well installation activities for these wells and Appendix B contains a copy of the well construction diagrams.

The objectives of this initial large-scale bedrock test, although similar to the subsequent test, were somewhat different. They were:

- Determine if the existing bedrock extraction wells at Site 1, plus well 1EW35, pumping at approximately their maximum sustainable rates, could reduce the water level in well 1GW12 to below the adjacent river level;
- Determine if pumping only the existing bedrock extraction wells at Site 1, plus well 1EW35, at approximately their maximum sustainable rates could achieve hydraulic containment in both the bedrock and alluvial aquifers at Site 1;
- Evaluate to what degree bedrock groundwater extraction at Site 1 produces a hydraulic effect at Site 10.

The design of the large-scale bedrock test required some modifications of the groundwater extraction system at Site 1 to maximize the pumping rates of the existing bedrock wells and to include the discharge from well 1EW35 in the treatment plant influent stream. Just before starting the large-scale test, the pumps in bedrock extraction wells 1EW29, 1EW31, 1EW32, and 1EW33 were replaced with higher capacity pumps. In addition, well 1EW35 was fitted with a temporary 80 gpm pump. In addition, the influent pipe near the groundwater treatment plant was excavated and a "Y" installed to accept flow from the temporary pipeline laid for the extracted water from well 1EW35.

After these modifications were made and the temporary transducers and dataloggers set up at strategic monitoring well locations, the large-scale bedrock test was initiated on November 28, 2001. However, after approximately 2 hours of pumping, the test was aborted because of the heavy suspended sediment load delivered to the treatment plant from well 1EW35 as a result of the increased pumping rate (i.e., 80 gpm). Although the test was aborted, the data collected during the 2 hours of pumping did yield some useful information. Primarily, the data suggested that the addition of well 1EW35 to the bedrock extraction well configuration would not likely achieve the desired objective and would also utilize between a quarter and a third of the treatment plant capacity by itself. Therefore, the approach and objectives of the large-scale test were refined and the test postponed until after the winter months. The aborted test is not further discussed.

3.5.2 Second Large-Scale Bedrock Aquifer Test

The second large-scale bedrock aquifer test was conducted between June 26 and July 10, 2001. There were two stages to the bedrock aquifer testing, a recovery stage and a pumping stage. These stages were completed sequentially and each had a 7-day duration.

Data loggers were installed in several wells and in the North Branch Potomac River prior to June 26, 2001. Two types of data loggers were used, Campbell multi-port loggers and In-Situ miniTrolls. The dataloggers were deployed as follows:

- Ten monitoring wells (1GW01, 1GW10, 1GW15, PWA01, PWC, GGW04, 10GW04, 10GW06, 10GW19, and 10GW27) were fitted with miniTroll data loggers. On July 2, 2001 there was a problem with the data logger installed in well 1GW10. Therefore, the logger from well 10GW04 was moved to well 1GW10 because well 1GW04 was considered a lower priority well for continuous water-level measurements.
- Pressure transducers were installed in wells GGW14, GGW15, 11GW11S and 11GW11D and a single Campbell Model 21X datalogger was used to monitor water levels in these wells.
- Pressure transducers were installed in wells 2GW02 and 2GW07 and a second Campbell Model 21X datalogger was used to monitor water levels in these at Site 2 wells.
- Pressure transducers were installed in well 1GW02 and at the upstream staff gauge in the North Branch Potomac River and a third Campbell 21X was used to monitor water levels at these locations at the western end of Site 1.
- Pressure transducers were installed in wells 10GW12 and 10GW26 and a forth Campbell Model 21X data logger was used to monitor water levels in these at Site 10 wells.

The locations of the data loggers and transducers that were installed during the Phase III Aquifer Test are shown in Figure 3-5. The data logger setup procedure included measuring and recording the depth to water in each well, calculating the water elevation, installing the transducer several feet below the water surface, setting the time and initial water level, and programming the logger to collect water-level data at 15-minute increments. The loggers began collecting data immediately following installation and continued collecting data at 15-minute intervals until both stages of bedrock aquifer testing were complete on July 10, 2001. The clocks on each of the data loggers were set to the same time so that the data records were synchronized.

At 2:30 p.m. on June 26, 2001, following installation and set up of all data loggers, all of the extraction wells (alluvial and bedrock) at Site 1were shut down. The extraction wells at Site 10 had been previously shut down due to an unrelated diesel release in the vicinity of Site 10. The shutdown of the Site 1 extraction wells marked the beginning of the 7-day recovery stage of the bedrock aquifer test. At 8:00 a.m. on July 3, 2001, after 7 days of passive recovery of the groundwater levels, the seven existing bedrock extraction wells at Site 1 were started up. This marked the beginning of the 7-day bedrock pumping test.

The pumping rates of the seven bedrock extraction wells were adjusted at the start of the test to produce the maximum sustainable flow of the pumps or wells. Water levels in the bedrock extraction wells were monitored by the treatment plant's programmable logic controller (PLC) to ensure that they did not drop to levels that would result in unplanned pump shutoffs. The readouts of the PLC were checked periodically to ensure all of the pumping wells were operating properly.

Three rounds of manual water-level measurements were taken at all of the monitoring and extraction wells designated for the long-term monitoring program plus several additional wells that are not in the long-term program. The first round was taken on June 26, 2001, the day before the extraction system was shut down to initiate the recovery portion of the test. This round of water levels was used to evaluate the water-level recovery data. The second round of water levels was taken just prior to beginning the pumping stage of the test to establish baseline conditions to compare with the induced groundwater level conditions. The third round of water levels was taken on July 10, 2001, just prior to ending the 7-day pumping stage of the bedrock aquifer test. During each of these manual water-level measurement events, water levels were also measured in all of the wells that contained data loggers to provide quality assurance checks on the performance of the data loggers.

In addition to the three comprehensive rounds of water level monitoring, water-level measurements were collected twice a day at the four well pairs listed below in order to evaluate any changes in the vertical hydraulic gradient in response to the bedrock pumping.

- 10GW01 and 10GW02
- 10GW20 and 10GW23
- 10GW21 and 10GW22
- GGW05 and GGW06

Manual water-level measurements in well 1GW02 and the upstream staff gauge also were collected twice a day because of the focused interest on the west end of Site 1. All manual water-level measurements were collected with electronic water-level indicators. Each measurement consisted of the distance (to the nearest 0.01 foot) between the water level in the well and the surveyed location on the top of the PVC or protective casing.

After completing the pumping stage of the test, the groundwater pumping at Site 1 and Site 10 was returned to its pre-test configuration. The results of this large-scale bedrock pumping test are discussed in Section 4.0.

Table 3-1

Chronology of Phase III Aquifer Testing Activities

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

Activity	Date
Extraction Well 10EW02 Installed and Yield-Tested	July 1998
Extraction Well 10EW02 Abandoned	July 1998
Monitoring Well 10GW07 Yield-Tested	July 1998
Extraction Well 10EW37 (Originally called 10EW06) Installed	July 1998
Monitoring Wells 10GW21 through 10GW24 Installed	July 1998
Direct-Push Sampling at Site 10 to Delineate Leading Edge of Alluvial Contaminant Plume	June 2000
Extraction Well 10EW38 Installed	July 2000
Monitoring Well 10GW25 Installed	July 2000
Experimental Extraction Well 1EW35 Installed	July 2000
Experimental Extraction Well 1EW35 Yield-Tested	August 2000
Monitoring Well 10GW27 Installed	September 2000
Monitoring Well 10GW26 Installed	October 2000
Initial Large-Scale Bedrock Pumping Test Started and Aborted	November 2000
Monitoring Wells 1GW02 and 1GW12 Pump Tested	February 2001
Monitoring Well 1GW02 Modified and Re-Tested	March - April 2001
Second Large-Scale Bedrock Pumping Test Conducted	June - July 2001
Unified Groundwater Flow Model Developed and Calibrated and Simulations Conducted	September - October 2001
Wells 10GW18, 10GW19, 10GW20, 10GW27, and 10EW38 Yield-Tested	September 2001

Table 3-2: Extraction Wells and Monitoring Wells Installed (or Modified) During Phase III Aquifer Testing Activities

Well ID	Aquifer	Date Installed	Effective Screened Interval
Site 1			
1EW35	Bedrock	July 2000	38.5 – 65 feet bgs
1GW02	Bedrock	April 2001	37 – 80 feet bgs
Site 10			
10EW37	Alluvial	July 1998	5 – 15 feet bgs
10EW38	Alluvial	July 2000	13 – 18 feet bgs
10GW21	Alluvial	July 1998	5 – 15 feet bgs
10GW22	Bedrock	July 1998	28 – 90 feet bgs
10GW23	Alluvial	July 1998	12 – 22 feet bgs
10GW24	Alluvial	July 1998	9 – 19 feet bgs
10GW25	Alluvial	July 2000	16 – 26 feet bgs
10GW26	Bedrock	October 2000	28 – 93 feet bgs
10GW27	Bedrock	October 2000	32 – 93 feet bgs

Table 3-3
MONITORING WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA[1]
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[2] (ft. msl)	Top of Casing Elevation[2] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[3]	Surface Casing		Top of Clayey Gravel Alluvium		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
GGW1	668.79	671.65	23	18	650.79	23	645.79	A	NA	NA	ND	ND	ND	ND
GGW2	669.01	672.07	84.5	70	599.01	80	589.01	B	31	638.01	8	661.01	23.5	645.51
GGW3	667.53	670.57	22	12	655.53	22	645.53	A	NA	NA	ND	ND	ND	ND
GGW4	667.51	670.66	82	70	597.51	80	587.51	B	24	643.51	8	659.51	22	645.51
GGW5	663.92	666.59	26	15.5	648.42	25.5	638.42	A	NA	NA	ND	ND	ND	ND
GGW6	663.93	666.75	81	70	593.93	80	583.93	B	33	630.93	13	650.93	28.5	635.43
GGW7	660.36	663.21	23	13	647.36	23	637.36	A	NA	NA	ND	ND	ND	ND
GGW8	660.27	663.21	80	70	590.27	80	580.27	B	30	630.27	10	650.27	24	636.27
GGW9	662.02	664.18	79	61.4	593.62	78.4	583.62	B	31.5	630.52	13	649.02	25	637.02
GGW10	664.07	667.40	31	16	648.07	31	633.07	A	NA	NA	ND	ND	29.5	634.57
GGW11	677.48	678.44	35	25	653.44	35	643.44	A	NA	NA	ND	ND	35	643.44
GGW12	683.81	684.47	43	33	651.47	43	641.47	A	NA	NA	ND	ND	43	641.47
GGW13	668.14	669.35	23	13	656.35	23	646.35	A	NA	NA	ND	ND	23	646.35
GGW14	670.30	669.90	20	10	659.90	20	649.90	A	NA	NA	ND	ND	20	649.90
GGW15	671.04	670.59	22	12	658.59	22	648.59	A	NA	NA	ND	ND	22	648.59
GGW16	670.94	670.58	21	11	659.58	21	649.58	A	NA	NA	ND	ND	21	649.58
1GW1	667.62	670.09	40	10	657.62	40	627.62	AB	NA	NA	9.5	658.12	24	643.62
1GW2	664.18	666.79	80	NA	NA	NA	NA	B	37	627.18	13	651.18	35	629.18
1GW3	665.95	668.25	40	10[5]	655.95	40	625.95	AB	24	641.95	13	652.95	29	636.95
1GW4	667.85	670.51	40	10[4]	657.85	40	627.85	B	29	638.85	10	657.85	27	640.85
1GW5	666.58	668.47	40	10[6]	656.58	40	626.58	B	30	636.58	18	648.58	ND	ND
1GW6	666.83	669.77	35	5[7]	661.83	35	631.83	B	24	642.83	10	656.83	20.5	646.33
1GW7	704.46	707.34	60	27	677.46	57	647.46	AB	NA	NA	44	660.46	50	654.46
1GW8	665.24	667.36	35	20	645.24	35	630.24	AB	NA	NA	17	648.24	ND	ND
1GW9	665.76	668.12	80	65	600.76	80	585.76	B	30	635.76	17.5	648.26	28	637.76
1GW10	664.44	667.38	82	70	594.44	80	584.44	B	33	631.44	12	652.44	26	638.44
1GW11	664.64	667.53	18	11	653.64	18	646.64	A	NA	NA	ND	ND	ND	ND

Table 3-3
MONITORING WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA[1]
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[2] (ft. msl)	Top of Casing Elevation[2] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[3]	Surface Casing		Top of Clayey Gravel Alluvium		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
1GW12	663.68	666.76	80	70	593.68	80	583.68	B	32.5	631.18	10	653.68	25	638.68
1GW13	665.59	668.43	121	111	554.59	121	544.59	B	33	632.59	13	652.59	26.5	639.09
1GW14	665.41	668.21	80.5	70.5	594.91	80.5	584.91	B	30	635.41	13	652.41	25	640.41
1GW15	664.88	666.74	120	71	593.88	81	583.88	B	36	628.88	12	652.88	29.5	635.38
1GW16	720.94	720.94	252	228	492.94	238	482.94	B	NA	NA	NA	NA	NA	720.94
1GW17	719.86	719.86	142	115	604.86	140	579.86	B	NA	NA	NA	NA	NA	719.86
1GW18	786.27	786.27	302	220	566.27	245	541.27	B	NA	NA	NA	NA	NA	754.27
1GW19	785.48	785.48	200	174	611.48	194	591.48	B	NA	NA	NA	NA	NA	753.48
1GW20	663.95	665.77	90	NA	NA	NA	NA	B	30	633.95	ND	ND	25	638.95
1GW21	664.05	666.25	90	NA	NA	NA	NA	B	31	633.05	ND	ND	24	640.05
1GW22	665.14	666.95	90	NA	NA	NA	NA	B	31	634.14	ND	ND	25	640.14
1GW23[11]	665.69	667.42	90	NA	NA	NA	NA	B	31	634.69	ND	ND	25	640.69
1GW24	665.53	667.33	26	10	655.53	25	640.53	A	NA	NA	ND	ND	25	640.53
1GW25	665.51	666.84	26	10	655.51	25	640.51	A	NA	NA	ND	ND	25	640.51
1GW26[12]	665.57	667.10	90	NA	NA	NA	NA	B	40	625.57	ND	ND	30	635.57
1GW27	666.43	667.97	90	NA	NA	NA	NA	B	40	626.43	ND	ND	25	641.43
1GW28	664.79	666.11	90	NA	NA	NA	NA	B	40	624.79	ND	ND	27	637.79
1GW29	665.60	667.10	90	NA	NA	NA	NA	B	40	625.60	ND	ND	27	638.60
1GW30	665.73	667.77	31	10	655.73	30	635.73	A	NA	NA	ND	ND	30	635.73
1GW31	666.13	668.42	31	10	656.13	30	636.13	A	NA	NA	ND	ND	30	636.13
1GW32	664.70	666.57	26	15	649.70	25	639.70	A	NA	NA	ND	ND	25	639.70
1GW33	666.00	668.18	25	9	657.00	24	642.00	A	NA	NA	ND	ND	24	642.00
1GW34	666.25	668.55	30	19	647.25	29	637.25	A	NA	NA	ND	ND	29	637.25
1GW35	668.70	671.14	29	18	650.70	28	640.70	A	NA	NA	ND	ND	28	640.70
1GW36	668.74	670.77	90	NA	NA	NA	NA	B	37	631.74	ND	ND	28	640.74
1GW37	667.81	670.19	29	18	649.81	28	639.81	A	NA	NA	ND	ND	28	639.81
1GW38	665.77	668.26	28	17	648.77	27	638.77	A	NA	NA	ND	ND	27	638.77

Table 3-3
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PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[2] (ft. msl)	Top of Casing Elevation[2] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[3]	Surface Casing		Top of Clayey Gravel Alluvium		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
1GW39	664.79	667.28	29	18	646.79	28	636.79	A	NA	NA	ND	ND	28	636.79
2GW1	665.86	667.04	40	10[5]	655.86	40	625.86	AB	24	641.86	13	652.86	30	635.86
2GW2	664.44	667.34	29.5	13	651.44	28	636.44	A	NA	NA	13.5	650.94	ND	ND
2GW3	663.86	666.62	27	11	652.86	26	637.86	A	NA	NA	19	644.86	27	636.86
2GW4	665.48	667.59	39	24	641.48	39	626.48	AB	NA	NA	13	652.48	ND	ND
2GW5	663.80	665.68	35	20	643.8	35	628.8	A	NA	NA	11.5	652.30	ND	ND
2GW6	664.08	666.11	80	65	599.08	80	584.08	B	49	615.08	13	651.08	37	627.08
2GW7	665.33	668.13	81	71	594.33	81	584.33	B	32	633.33	14	651.33	27	638.33
3GW1	663.25	666.00	35	5[7]	658.25	35	628.25	AB	24	639.25	12.5	650.75	28	635.25
3GW2	662.28	665.15	27	10	652.28	25	637.28	A	NA	NA	13	649.28	ND	ND
3GW3	678.73	681.91	42.5	24	654.73	39	639.73	A	NA	NA	25	653.73	42.5	636.23
3GW4	667.12	669.47	90.5	75.5	591.62	90.5	576.62	B	47	620.12	13	654.12	32	635.12
4GW1	664.83	667.61	28	12	652.83	27	637.83	A	NA	NA	18.5	646.33	ND	ND
5GW1	753.70	756.31	60	20[8]	733.70	60	693.70	A	50	703.70	ND	ND	ND	ND
5GW2	685.84	688.60	50	20[9]	665.84	50	635.84	B	37	648.84	ND	ND	33	652.84
5GW3	686.29	689.16	50	20[10]	666.29	50	636.29	B	35	651.29	ND	ND	34.5	651.79
5GW4	685.48	688.74	83	73	612.48	83	602.48	B	39.5	645.98	ND	ND	33	652.48
5GW5	685.63	688.89	76	65	620.63	75	610.63	B	40	645.63	28	657.63	34	651.63
5GW6	753.37	755.75	90	80	673.37	90	663.37	B	64	689.37	ND	ND	59	694.37
5GW7	685.87	688.51	36	26	659.87	36	649.87	A	NA	NA	ND	ND	36	649.87
5GW8	685.67	688.70	35.7	25.3	660.37	35.3	650.37	A	NA	NA	ND	ND	35	650.67
5GW9	686.78	689.94	34	24	662.78	34	652.78	A	NA	NA	ND	ND	34	652.78
5GW10	687.75	689.47	78	63	624.75	78	609.75	B	30	657.75	16	671.75	24.5	663.25
5GW11	687.64	689.71	25	15	672.64	25	662.64	A	NA	NA	16	671.64	24	663.64
5GW12	677.46	679.41	88	63	614.46	88	589.46	B	29	648.46	15	662.46	24	653.46
5GW13	677.04	679.43	24	14	663.04	24	653.04	A	NA	NA	15	662.04	24	653.04
5GW14	687.20	688.90	70	NA	NA	NA	NA	B	40.5	646.70	ND	ND	34	653.20

Table 3-3
MONITORING WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA[1]
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[2] (ft. msl)	Top of Casing Elevation[2] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[3]	Surface Casing		Top of Clayey Gravel Alluvium		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
5GW15	677.55	678.98	25	9	668.55	24	653.55	A	NA	NA	ND	ND	24	653.55
5GW16	676.84	678.05	60	NA	NA	NA	NA	B	31	645.84	ND	ND	24	652.84
5GW17	674.18	676.43	25	9	665.18	24	650.18	A	NA	NA	ND	ND	24	650.18
7GW1	NS	NS	64	10	NA	60	NA	B	NA	NA	ND	ND	1.5	NA
10EW5	664.65	664.65	20	9	655.65	19	645.65	A	NA	NA	ND	ND	19	645.65
10GW1	667.52	669.40	90	NA	NA	NA	NA	B	31	636.52	ND	ND	24	643.52
10GW2	667.65	669.59	25	9	658.65	24	643.65	A	NA	NA	ND	ND	24	643.65
10GW3	666.84	668.49	90	NA	NA	NA	NA	B	30	636.84	ND	ND	20	646.84
10GW4	667.31	668.68	90	NA	NA	NA	NA	B	30	637.31	ND	ND	22	645.31
10GW5	666.56	668.25	90	NA	NA	NA	NA	B	30	636.56	ND	ND	23	643.56
10GW6	666.46	667.96	90	NA	NA	NA	NA	B	30	636.46	ND	ND	19	647.46
10GW7	664.14	666.18	23	8.5	655.64	18.5	645.64	A	NA	NA	ND	ND	19.5	644.64
10GW8	667.85	669.86	20	9	658.85	19	648.85	A	NA	NA	ND	ND	19	648.85
10GW9	668.95	670.83	23.5	8.5	660.45	23.5	645.45	A	NA	NA	ND	ND	23.5	645.45
10GW10	669.26	671.06	23	6	663.26	21	648.26	A	NA	NA	ND	ND	25	644.26
10GW12	666.54	668.87	24	13	653.54	23	643.54	A	NA	NA	ND	ND	23	643.54
10GW13	664.96	667.31	16	5	659.96	15	649.96	A	NA	NA	ND	ND	15	649.96
10GW14	667.02	669.33	21	10	657.02	20	647.02	A	NA	NA	ND	ND	20	647.02
10GW15	665.82	667.81	21	10	655.82	20	645.82	A	NA	NA	ND	ND	20	645.82
10GW16	665.55	667.70	18	7	658.55	17	648.55	A	NA	NA	ND	ND	17	648.55
10GW17	666.73	669.04	18	7	659.73	17	649.73	A	NA	NA	ND	ND	17	649.73
10GW18	666.30	668.42	90	NA	NA	NA	NA	B	35	631.30	ND	ND	22	644.30
10GW19	669.31	670.35	90	NA	NA	NA	NA	B	37	632.31	ND	ND	27	642.31
10GW20	666.34	667.65	90	NA	NA	NA	NA	B	33	633.34	ND	ND	23	643.34
10GW21	664.08	665.03	15	5	659.08	15	649.08	A	NA	NA	ND	ND	15	649.08
10GW22	664.66	665.88	90	NA	NA	NA	NA	B	28	636.66	ND	ND	25	639.66
10GW23	666.44	667.48	22	12	654.44	22	644.44	A	NA	NA	ND	ND	22	644.44

Table 3-3
MONITORING WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA[1]
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[2] (ft. msl)	Top of Casing Elevation[2] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[3]	Surface Casing		Top of Clayey Gravel Alluvium		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
10GW24	665.50	666.22	19	9	656.50	19	646.50	A	NA	NA	ND	ND	19	646.50
10GW25	666.93	668.78	26	16	650.93	26	640.93	A	NA	NA	ND	ND	26	640.93
10GW26	666.68	667.94	93	NA	NA	NA	NA	B	28	638.68	ND	ND	23	643.68
10GW27	664.48	666.42	93	NA	NA	NA	NA	B	32	632.48	ND	ND	25	639.48
PWA1	669.63	671.23	78	63	606.63	78	591.63	B	NA	NA	22	647.63	47	622.63
PWA2	669.39	671.68	35	20	649.39	35	634.39	A	NA	NA	20	649.39	ND	ND

NOTES:
[1]All non-survey data for monitoring wells installed during previous investigations were taken from *Draft Interim Remedial Investigation for Allegany Ballistics Laboratory*, Roy F. Weston, Inc. (October 1989).
[2]Surveyed in August 1992, November 1994, or May 1996. All elevations are in feet above mean sea level (ft. msl).
[3]Screened Unit: A = Alluvium; B = Bedrock; AB = well screened across the alluvium/bedrock contact.
[4]Surface casing shrouds a portion of the screen; effective screen interval is 29-40 feet bgs.
[5]Surface casing shrouds a portion of the screen; effective screen interval is 24-40 feet bgs.
[6]Surface casing shrouds a portion of the screen; effective screen interval is 30-40 feet bgs.
[7]Surface casing shrouds a portion of the screen; effective screen interval is 24-35 feet bgs.
[8]Surface casing shrouds a portion of the screen; effective screen interval is 50-60 feet bgs.
[9]Surface casing shrouds a portion of the screen; effective screen interval is 37-50 feet bgs.
[10]Surface casing shrouds a portion of the screen; effective screen interval is 35-50 feet bgs.
[11]Renamed 1EW34 in December 1996.
[12]Renamed 1EW28 in December 1996.

NA = Not applicable; ND = Not Determined (no soil sampling performed); NS = Not Surveyed

Table 3-4
EXTRACTION WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[1] (ft. msl)	Top of Casing Elevation[1] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[2]	Surface Casing		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
1EW1	663.36	663.36	29	18	645.36	28	635.36	A	NA	NA	28	635.36
1EW2	666.30	666.30	29	18	648.30	28	638.30	A	NA	NA	28	638.30
1EW3	666.18	666.18	28	17	649.18	27	639.18	A	NA	NA	27	639.18
1EW4	666.07	666.07	28	17	649.07	27	639.07	A	NA	NA	27	639.07
1EW5	665.74	665.74	29	18	647.74	28	637.74	A	NA	NA	28	637.74
1EW6	666.36	666.36	29	18	648.36	28	638.36	A	NA	NA	28	638.36
1EW7	666.81	666.81	26	15	651.81	25	641.81	A	NA	NA	25	641.81
1EW8	666.78	666.78	30	19	647.78	29	637.78	A	NA	NA	29	637.78
1EW9	667.30	667.30	28	17	650.30	27	640.30	A	NA	NA	27	640.30
1EW10	667.43	667.43	28	17	650.43	27	640.43	A	NA	NA	27	640.43
1EW11	668.37	668.37	30	19	649.37	29	639.37	A	NA	NA	29	639.37
1EW12	667.38	667.38	28	17	650.38	27	640.38	A	NA	NA	27	640.38
1EW13	667.77	667.77	29	18	649.77	28	639.77	A	NA	NA	28	639.77
1EW14	666.89	666.89	28	17	649.89	27	639.89	A	NA	NA	27	639.89
1EW15	667.66	667.66	30	19	648.66	29	638.66	A	NA	NA	29	638.66
1EW16	666.77	666.77	27	16	650.77	26	640.77	A	NA	NA	26	640.77
1EW17	667.38	667.38	29	18	649.38	28	639.38	A	NA	NA	28	639.38
1EW18	666.70	666.70	28	17	649.70	27	639.70	A	NA	NA	27	639.70
1EW19	667.36	667.36	30	19	648.36	29	638.36	A	NA	NA	29	638.36
1EW20	666.16	666.16	30	19	647.44	29	637.44	A	NA	NA	29	637.44
1EW21	666.41	666.41	33	22	644.41	32	634.41	A	NA	NA	32	634.41
1EW22	666.62	666.62	30	19	647.62	29	637.62	A	NA	NA	29	637.62
1EW23	675.62	675.62	44	33	642.62	43	632.62	A	NA	NA	43	632.62

Table 3-4
EXTRACTION WELL CONSTRUCTION DETAILS AND BOREHOLE LITHOLOGIC DATA
PHASE III AQUIFER TESTING
ALLEGANY BALLISTICS LABORATORY

Well	Ground Elevation[1] (ft. msl)	Top of Casing Elevation[1] (ft. msl)	Depth of Boring (ft)	Screen Top		Screen Bottom		Screened Unit[2]	Surface Casing		Top of Bedrock	
				Depth (ft)	Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)		Depth (ft)	Bottom Elevation (ft. msl)	Depth (ft)	Elevation (ft. msl)
1EW24	676.18	676.18	39	28	648.18	38	638.18	A	NA	NA	38	638.18
1EW25	674.88	674.88	40	29	645.88	39	635.88	A	NA	NA	39	635.88
1EW26	675.34	675.34	40	29	646.34	39	636.34	A	NA	NA	39	636.34
1EW27	666.07	666.07	26	15	651.07	25	641.07	A	NA	NA	25	641.07
1EW28[3]	665.57	667.10	90	NA	NA	NA	NA	B	40	625.57	30	635.57
1EW29	666.55	666.55	90	NA	NA	NA	NA	B	37	629.55	29	637.55
1EW30	666.88	666.88	90	NA	NA	NA	NA	B	38	628.88	29	637.88
1EW31	666.33	666.33	90	NA	NA	NA	NA	B	38	628.33	26	640.33
1EW32	666.05	666.05	90	NA	NA	NA	NA	B	38	628.05	28	638.05
1EW33	666.18	666.18	90	NA	NA	NA	NA	B	37	629.18	28	638.18
1EW34[4]	665.69	667.42	90	NA	NA	NA	NA	B	31	634.69	25	640.69
1EW35	674.06	676.43	65	NA	NA	NA	NA	B	38.5	635.56	38	636.06
10EW35[5]	666.21	666.21	21	10	656.21	20	646.21	A	NA	NA	20	646.21
10EW36[6]	668.77	668.47	25	10	658.77	25	643.77	A	NA	NA	25	643.77
10EW37	663.83	666.93	15	5	658.83	15	648.83	A	NA	NA	15	648.83
10EW38	666.02	665.50	19	14	652.02	19	647.02	A	NA	NA	19	647.02
10EW5	664.65	664.65	20	9	655.65	19	645.65	A	NA	NA	19	645.65

NOTES:
[1]Surveyed in December 1996. All elevations are in feet above mean sea level (ft msl).
[2]Screened Unit: A = Alluvium; B = Bedrock.
[3]Well formerly named 1GW26.
[4]Well formerly named 1GW23.
[5]Well formerly named 10EW1.
[6]Well formerly named 10GW11.
NA = Not applicable; ND = Not Determined (no soil sampling performed)

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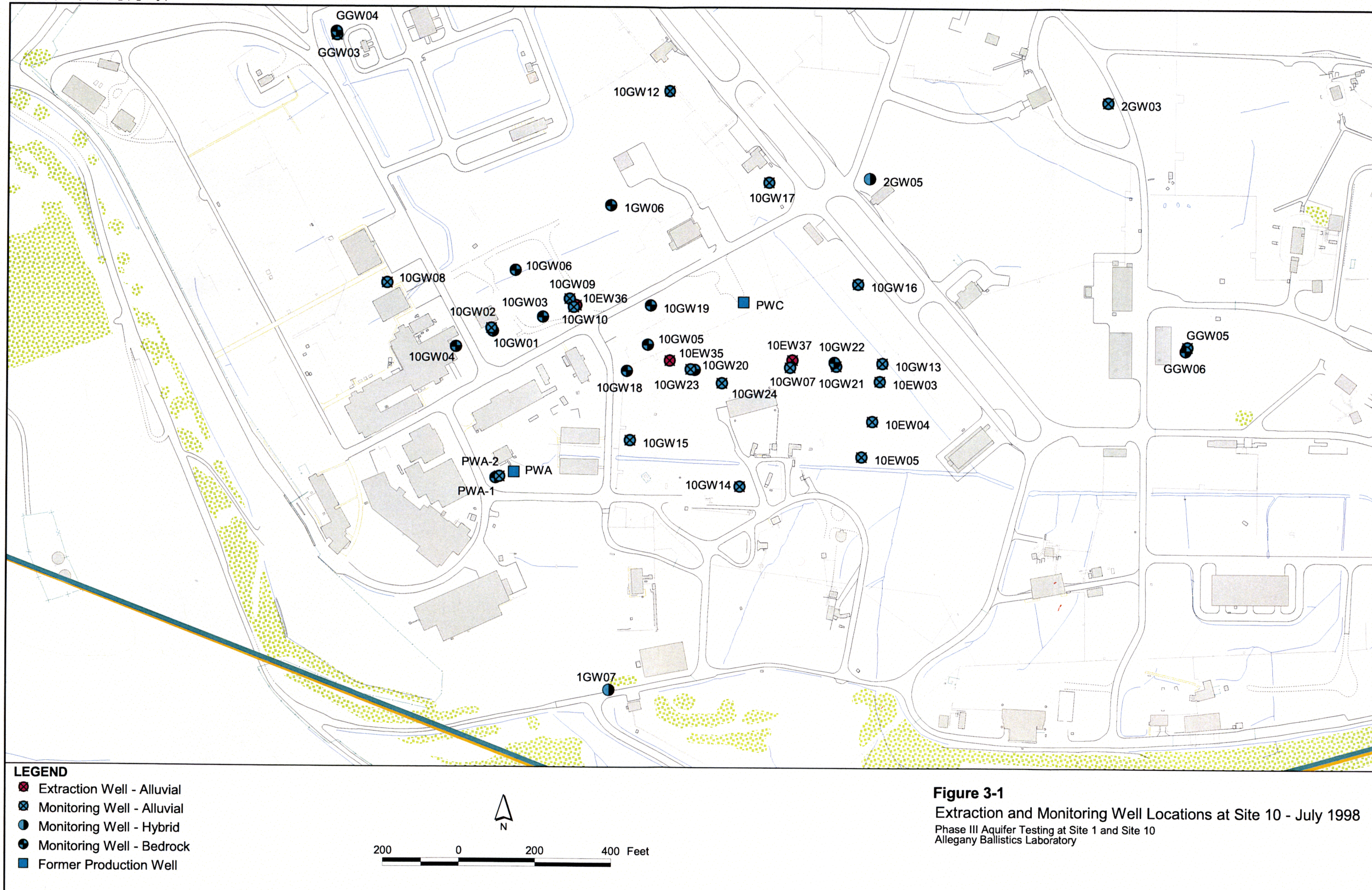

Figure 3-1
Extraction and Monitoring Well Locations at Site 10 - July 1998
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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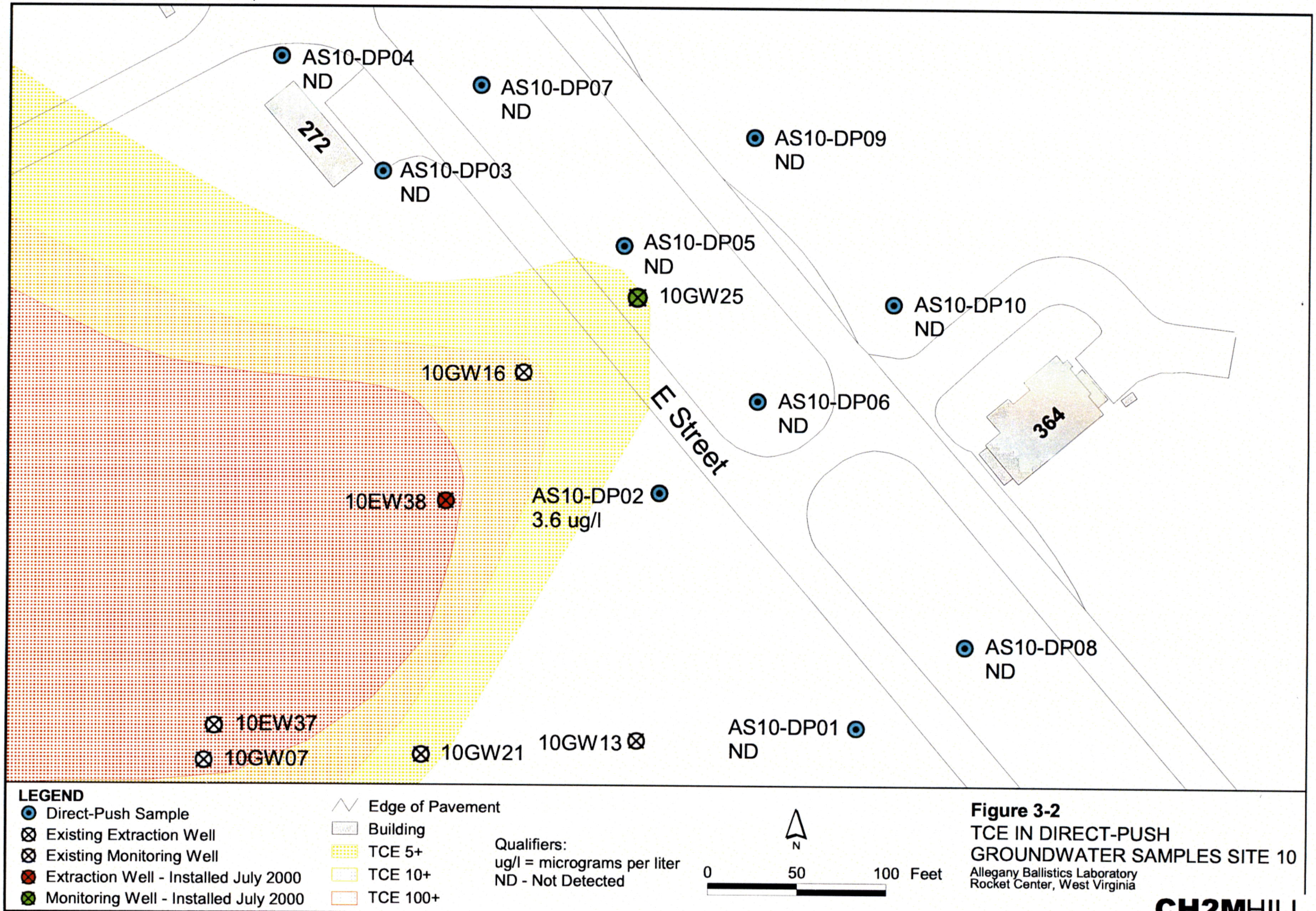

Figure 3-2
TCE IN DIRECT-PUSH GROUNDWATER SAMPLES SITE 10
Allegany Ballistics Laboratory
Rocket Center, West Virginia

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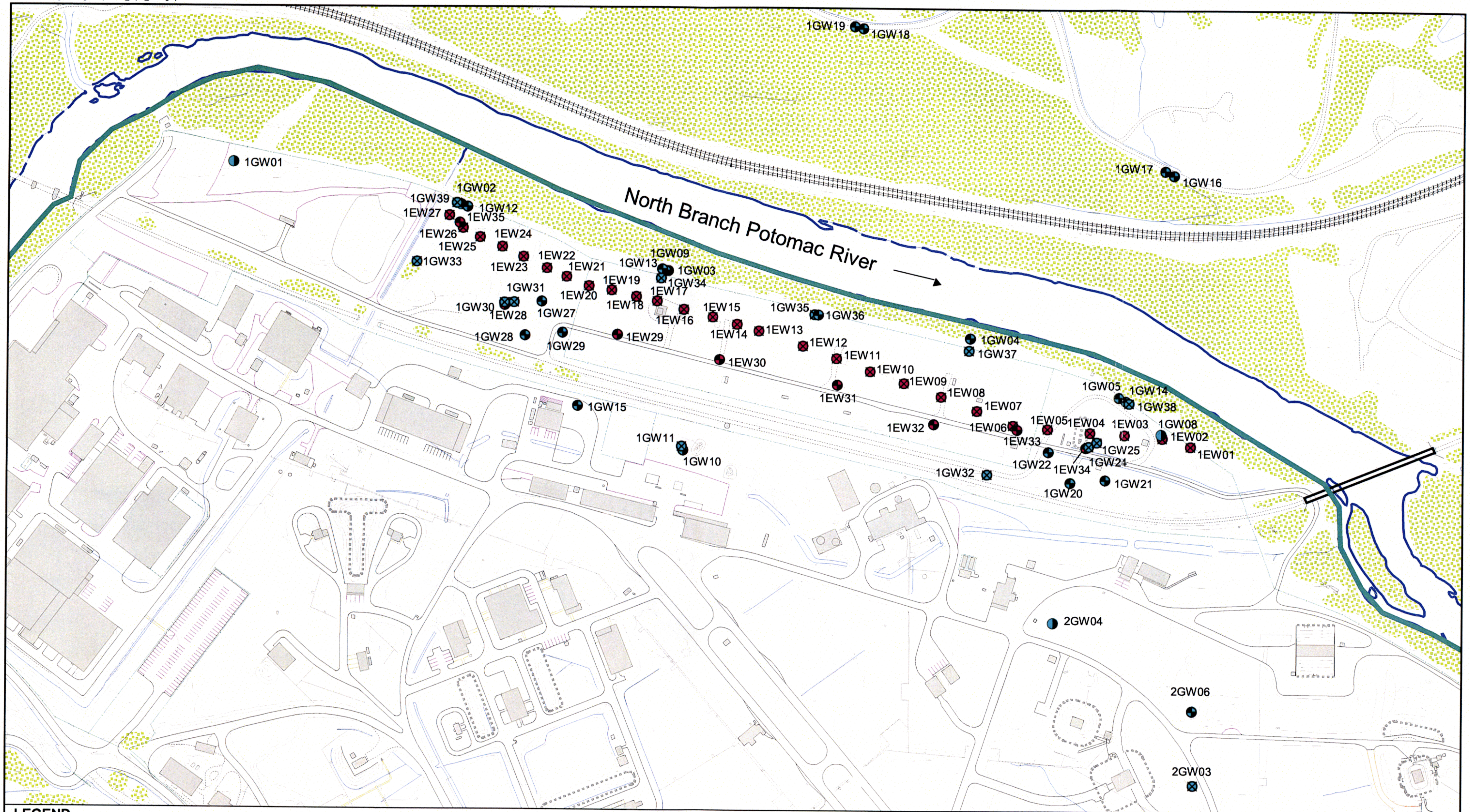

LEGEND

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Alluvial
- Monitoring Well - Hybrid
- Monitoring Well - Bedrock

N

200 0 200 400 Feet

Figure 3-3

Extraction and Monitoring Well Locations at Site 1

Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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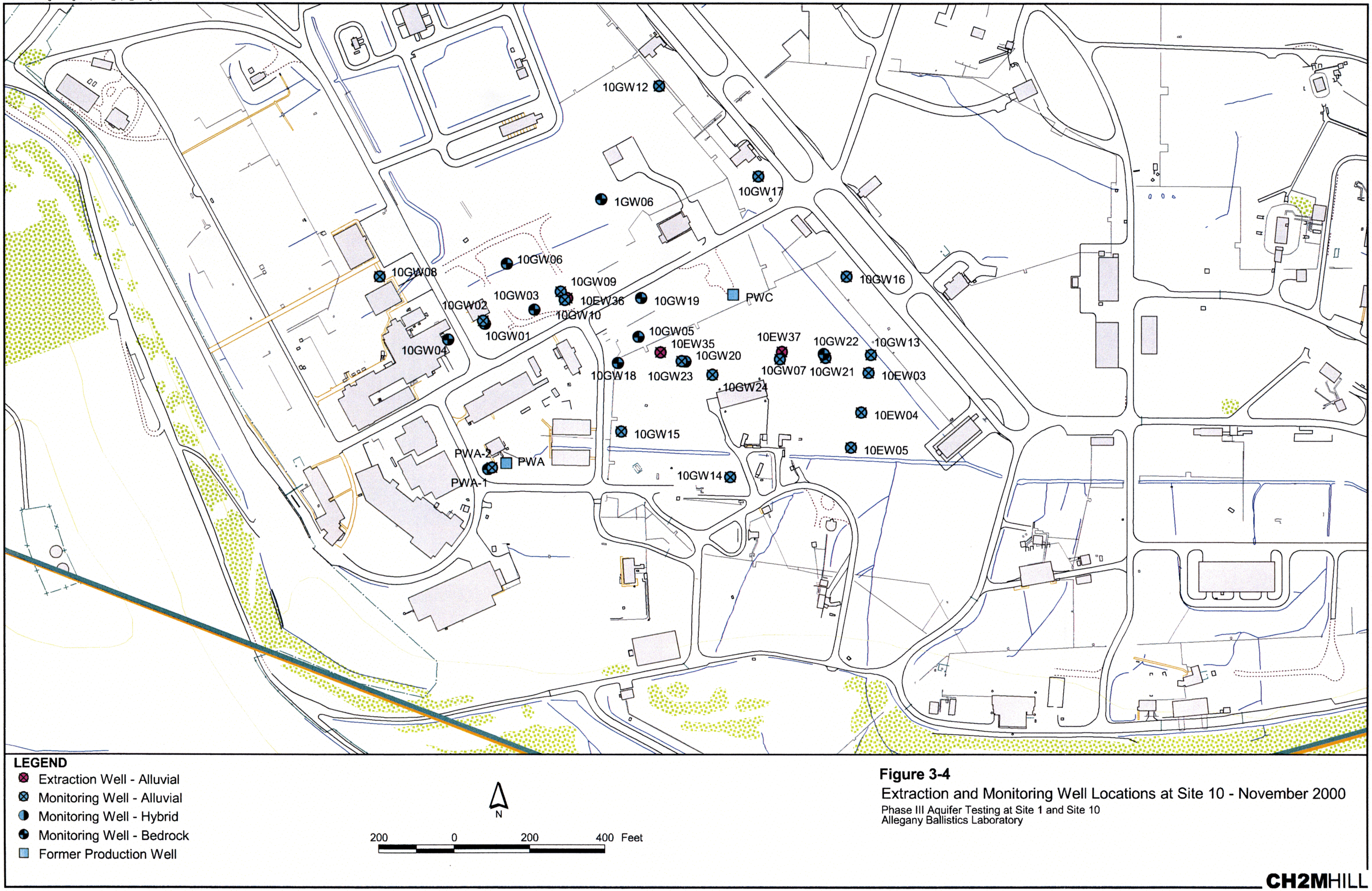

Figure 3-4
Extraction and Monitoring Well Locations at Site 10 - November 2000
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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4.0 Bedrock Pumping Test Results

4.1 Introduction

4.1.1 Test Objectives

As discussed in Section 3.0, a large-scale bedrock pumping test was conducted at sites 1 and 10 over the two-week period from June 26, to July 10, 2001. The test was run in two stages. First, the alluvial and bedrock extraction wells at Site 1 were turned off for seven days, allowing the aquifers to recover as nearly as practical to natural flow conditions (the extraction wells at site 10 had already been off for several days for unrelated reasons). Then the seven bedrock extraction wells at Site 1 were turned on for seven days at their maximum sustainable pumping rates. The test procedure (described in greater detail in Section 3) was designed to achieve the following objectives:

- Determine whether satisfactory hydraulic containment of contaminated groundwater could be attained in both the alluvial and bedrock aquifers at Site 1 by pumping the seven bedrock extraction wells only. A positive result could lead to significant savings in operational costs if operation of the 27 alluvial extraction wells was found to be unnecessary.
- Characterize the effects of pumping the Site-1 extraction system on water levels and hydraulic gradients at Site 10. Specifically, it was to be determined whether drawdown propagating through the bedrock from Site 1 was responsible for the observed downward hydraulic gradients that had been observed at Site 10 since the startup of the groundwater remediation system. If the test revealed a significant hydraulic response at Site 10, the pathways of drawdown propagation between the sites would be identified.
- Produce data sets that could serve as a useful calibration target for the development and calibration of a unified groundwater flow model of Site 1 and Site 10.

4.1.2 Types of Data Produced

The large-scale bedrock test produced results in the form of water-level measurements at a substantial number of wells located in and around sites 1 and 10 and at two locations in the North Branch Potomac River. Water-level measurements were collected in three ways:

- Continuous records of water-level variations collected automatically by temporary pressure transducers and data loggers and by permanent pressure transducers monitored by the treatment plant PLC,
- Intermittent manual measurements of water levels in well pairs showing the vertical head differences between the alluvial and bedrock aquifers at specific points, and
- Three comprehensive rounds of synoptic water-level measurements at monitoring wells in and around sites 1 and 10.

Continuous records (at 15-minute intervals) of water-level variations with time were collected automatically by temporary data loggers installed in 18 monitoring wells and in the river at the upstream staff gauge. In addition, continuous water-level records were collected by dedicated pressure transducers in the 27 alluvial extraction wells at Site 1, three alluvial extraction wells at Site 10, ten monitoring wells along the river at Site 1, and in the river at the downstream staff gauge. The main reason for collecting such a large number of continuous records was to identify the areal pattern of hydraulic response in the bedrock aquifer to pumping at Site 1. Consequently, most of the temporary data loggers were installed in bedrock wells. However, a few were also installed in alluvial wells near monitored bedrock wells so that the differences in alluvial and bedrock response, and possible changes in vertical gradients, could be observed. The response of the alluvial aquifer was also revealed by existing dedicated pressure transducers in alluvial extraction wells. Because these wells were not pumped during the bedrock test, they could be used as monitoring points.

To supplement the continuous water-level data, intermittent measurements were made by hand in ten monitoring wells. These ten wells formed five pairs of closely-spaced wells where measurements would show the differences in head between the alluvial and bedrock aquifers. Water levels in these wells were measured seven times during the four days (July 3 to July 6) following the start of the bedrock pumping stage of the test. The purpose was to look for reversals in vertical gradients that might be caused by high-rate pumping of the Site-1 bedrock wells.

Three comprehensive rounds of synoptic water-level measurements were made during the test. In each round, water levels were measured in 119 wells and at the two staff gauges located in the North Branch Potomac River upstream and downstream of Site 1. The three rounds were conducted on June 26, July 2, and July 10, 2001. The first round occurred just before the extraction wells at Site 1 were turned off to start the recovery stage of the test. The second round was performed at the end of the recovery stage, the day before the Site-1 bedrock extraction wells were started up. The third round was completed at the end of the bedrock pumping stage, just before extraction systems at Site 1 and Site 10 were returned to normal operation. The synoptic water-level data sets were used to prepare potentiometric surface maps representing stabilized flow conditions in both aquifers at these critical stages of the test. The potentiometric surface maps were used as targets for calibrating the groundwater flow model (Section 5.0). The water-level differences from one stage of the test to another were also mapped to show the areal distributions of recovery and drawdown in each aquifer.

4.1.3 Methods of Analysis

The large-scale bedrock pumping test was not a traditional aquifer test and was not analyzed in the traditional way. Traditional aquifer tests are usually conducted by pumping one well at a time and observing drawdown in nearby observation wells. The results are then evaluated by fitting a simple one-dimensional model of well hydraulics, such as the Theis equation, to the drawdown observations and determining a set of aquifer parameters that gives the best match between the theoretical and measured time-drawdown curves. The aquifer parameter estimates derived from such a small-scale test may then be extrapolated to a larger scale by using them in a groundwater flow model of the site.

This traditional aquifer testing process is limited by the assumptions that are inherent in the simple one-dimensional models of well hydraulics. They assume that the aquifer has uniformly distributed properties, and generally that the properties are horizontally isotropic. These assumptions are not valid for the aquifers at ABL. To perform the traditional analysis, knowing that the conditions of homogeneity and isotropy were not met, would produce erroneous results of unknown usefulness. This is especially true in a situation where seven bedrock extraction wells in a 1,600-foot alignment were pumped simultaneously.

Instead of using the traditional process, the test results were evaluated by applying them directly to address the test objectives. The first objective was to determine whether bedrock pumping alone would be enough to hydraulically contain contaminated groundwater in both the alluvial and bedrock aquifers at Site 1. This question was answered by direct observation of the test results. The second objective, characterizing hydraulic interactions between sites 1 and 10, was addressed by direct observation of the continuous water-level records, and by plotting the observed drawdown and recovery distributions. The third objective of the test was to produce calibration target data that would permit development of a realistic unified groundwater flow model of the site. Calibration of a groundwater flow model is analogous to the traditional procedures of aquifer test analysis, in which a mathematical model is adjusted to produce the best possible fit to the test results. In this case, however, the model used is not a simple one-dimensional equation, but a three-dimensional numerical model that can accommodate non-uniformity and anisotropy of the aquifer parameters. The result of the model calibration process is a set of quantitative spatially variable estimates of the aquifer parameters over the entire area covered by the model. The development of the groundwater flow model and its calibration to the test data are described in Section 5.

4.2 Rainfall and River Level Variations

Under ideal conditions, an aquifer test would be conducted at a time when no hydrologic activity was taking place except for the controlled pumping rate changes of the test. Any observed changes in water levels could then be attributed directly to the test activities. Conditions during the bedrock pumping test were not ideal because of rainfall and river-level fluctuations that occurred before and during the test. Figure 4-1 shows the rainfall and river-level records for the month of June and the first 10 days of July, 2001. The bedrock pumping test was performed from June 26 through July 10.

As the figure shows, there were two substantial rain events in the weeks leading up to the test. In both cases, the rain storm was followed by a rise in river levels that lagged about two days behind the rain. Since the river flow is partly controlled by a dam approximately 25 miles upstream of ABL, it is likely that the river-level fluctuations were caused by a combination of flow regulation at the dam, and runoff and groundwater inflows that occurred between the dam and Site 1. Figure 4-1 shows that the river levels responded to these influences by rising and falling several feet in a period of one or two days.

Groundwater levels in the aquifers adjacent to the river are also affected by rainfall. They may rise fairly rapidly during and after a storm, but require a longer recession period than the river does to return to their pre-storm levels. Consequently, a general decline in groundwater levels was observed during the first week of the bedrock test (i.e., the recovery stage). It was believed to be caused by the rainfall totaling about 2.13 inches that occurred from June 21 to June 23.

4.3 Continuous Water-Level Records

4.3.1 Records from the Temporary Data Loggers

Temporary data loggers were installed in 18 monitoring wells and at the upstream staff gauge in the North Branch Potomac River to record water levels during the two-week bedrock test. The records obtained from these wells are shown on the map of the study area in Figure 4-2. To provide a sense of the spatial variations in aquifer response to the test, the records are presented as small graphs inset into the site map. Larger versions of the data plots are proved in Appendix D.

The records for bedrock monitoring wells 1GW10 and 1GW15 are shown in the upper central part of Figure 4-2. The water levels in these two wells responded in the way that would be expected for an area that was strongly affected by pumping of the Site 1 bedrock extraction wells. At the start of the recovery period, the water level in well 1GW15 rose approximately 3.5 feet in the first day after the extraction system was shut off on June 26. For the following six days of the recovery period the levels in well 1GW15 remained constant or declined slightly. The reason for the decline was the general reduction in groundwater levels following the rainfall that preceded the test. On July 2, the water level in well 1GW15 responded sharply to the start of bedrock pumping, declining more than 10 feet in the first day. The record for well 1GW10 is incomplete because the data logger initially installed in that well was defective, as noted in Section 3.5.2. It was replaced on July 2, before the start of the bedrock pumping stage of the test. The drawdown response observed in well 1GW10 was very similar to the response at well 1GW15, but the magnitude was only about two thirds as great.

Aquifer response at the west end of Site 1 is illustrated by the water-level records for wells 1GW01 and 1GW02 in Figure 4-2. They are presented together with the river level record from the upstream gauge because they tracked the river-level fluctuations quite closely. Well 1GW01 is a hybrid monitoring well; it is screened in both the alluvium and the upper 16 feet of bedrock. Because the hybrid screening of well 1GW01 makes its data ambiguous, that well is seldom monitored. However, it is the only existing monitoring point located directly west of the Site-1 extraction system, so its response was monitored during this test. Well 1GW02 is a pure bedrock monitoring well located at the west end of the Site-1 extraction system between the extraction wells and the river. Both of these monitoring wells mirrored the behavior of the river very closely and showed no evident response to manipulation of the extraction wells, either during the recovery stage or the pumping stage of the test. This suggests that the area near the river west of Site 1 has a very good hydraulic connection to the river, but is somewhat isolated from the groundwater extraction system.

Aquifer response in the area east of Site 1 is shown in Figure 4-2 by the water-level records at wells 2GW02 and 2GW07. Because these wells are fairly close to the river, the river-level record from the downstream gauge is shown for comparison. Water levels in alluvial well 2GW02 showed little apparent response to either the river fluctuations or the pumping test.

Instead, there was a gradual decline in water level of about half a foot during the two-week test. In contrast, bedrock well 2GW07 responded fairly clearly to the initial shutdown of the Site 1 extraction system and to the bedrock pumping stage of the test. The magnitude of the drawdown at well 2GW07 during the pumping segment was about 1 foot, even though this well is approximately 1,000 feet east of the nearest bedrock extraction well.

Figure 4-2 also shows three sets of water-level records from wells closer to Site 10. On the western side of Site 10, the records for wells PWA01, 10GW19, and GGW04 are shown. None of these well showed any clear response to the pumping test. Instead, they reflect the general decline in groundwater levels that was noted over the test period, punctuated by brief water-level increases corresponding to rainfall events. These are all bedrock wells, and it is apparent that the bedrock aquifer in these areas did not respond to hydraulic influences from Site 1 at the pumping rates used in this test.

A similar lack of hydraulic response is seen in wells 10GW06, 10GW12, and 10GW26, all located in the central and northern portions of Site 10. The two bedrock wells in this group are 10GW06 and 10GW26. They showed responses to rainfall events, but no evident responses to the test. Well 10GW12 is an alluvial monitoring well. It showed no evident responses to either the pumping test or the rain events. Instead, it showed a fairly steady decline in water levels of slightly more than 1 foot over the two-week period.

Figure 4-2 shows that the water levels in the two bedrock wells monitored on the northeast side of Site 10, wells PWC and 10GW27, responded clearly to the bedrock test. Both of those wells showed increasing water levels at the start of the recovery period and decreasing levels at the start of the pumping period. These responses are superimposed on the general water-level decline of approximately 1 foot in two weeks that was seen at the non-responding wells. These two wells are as far, or farther, from Site 1 than many of the wells that showed no response to the test. This suggests that a relatively high-transmissivity pathway must exist in the bedrock between Site 1 and the northeast corner of Site 10.

4.3.2 Records from Permanent Pressure Transducers

Permanent pressure transducers are installed in all of the alluvial extraction wells at Site 1 and Site 10 for control of the pumping rates in those wells. Because the alluvial wells were not pumped during the bedrock test, the water-level records collected by those transducers were used as monitoring data for the test. In addition, there are ten monitoring wells near the river at Site 1 that have permanent pressure transducers from which water levels are continuously recorded. Five of the wells are in the alluvium and five are in the bedrock. The responses of these 37 wells were helpful in showing how the aquifers at Site 1 responded to bedrock pumping.

4.3.2.1 Site 1 Monitoring Wells Near the River

4.3.2.1.1 Alluvial Monitoring Wells

Figure 4-3 shows the water-level records from the five alluvial monitoring wells spaced from west to east along the North Branch Potomac River adjacent to Site 1. Since this line of wells spans the width of Site 1, river levels from both the upstream and downstream gauges are shown in Figure 4-3 for reference. The record for the upstream river gauge was supplied by a temporary data logger installed for the bedrock test. The first few days of that record are rather rough because the data logger was initially set to record to an accuracy of only one decimal place.

Well 1GW39, the alluvial monitoring well on the west end of the line, does not appear to have responded to the bedrock test. Instead, it tracked the river levels almost exactly. This is very similar to the behavior shown for wells 1GW02 and 1GW01, shown in Figure 4-2. Apparently, both the alluvial and bedrock aquifers on the west end of Site 1 are hydraulically well connected with the river and not well connected with the rest of Site 1.

Well 1GW34, the second alluvial monitoring well from the west end of Site 1, responded very clearly to both the recovery and the bedrock pumping stages of the test. Conversely, it seems to have been practically unaffected by changes in river levels.

The next well in the line, 1GW35, responded slowly to the shutdown of the extraction system at the start of the recovery period, but did not respond to bedrock pumping. This response probably indicates that the alluvial aquifer at well 1GW35 is affected by pumping of the alluvial extraction wells, but is not significantly influenced by bedrock extraction.

Well 1GW37, the second well from the east end of Site 1, responded in both stages of the bedrock test. The recovery of the water level in that well was initially rapid, when the system was turned off, and then continued slowly for the rest of the recovery period. This slow portion of the recovery curve is contrary to the general declining trend of groundwater levels and appears unrelated to the river levels. Most likely, it is a slow response to the cessation of pumping in the alluvial extraction wells. During the second stage of the test, the water level in well 1GW37 responded quickly to pumping in the bedrock extraction wells. This well showed only a minimal influence from changes in river levels, but responded quickly to bedrock pumping (as evidenced by a quick water-level decline when the bedrock wells were turned on) and slowly to alluvial pumping (as evidenced by the slow recovery after system shutdown).

At the east end of Site 1, well 1GW38 responded slowly to the shutdown of the alluvial extraction wells, and appeared to be only slightly affected by bedrock pumping or changes in river level.

4.3.2.1.2 Bedrock Monitoring Wells

Figure 4-4 shows the water-level records from the five bedrock monitoring wells spaced from west to east along the river adjacent to Site 1. Also shown are the river-level records from the upstream and downstream gauges.

Well 1GW12, at the west end of the line, showed water-level changes almost identical to those recorded in the river. In spite of the obviously close relationship between this well and the river, its water levels were consistently about 0.37 feet higher than the river level at the upstream gauge. Further, well 1GW12 was not visibly affected by the bedrock pumping test. This suggests that, like the alluvial aquifer in this area, the bedrock is better-connected to the river than with the rest of Site 1. Further, its water level may suggest an upwelling of deep bedrock groundwater in that area.

The second bedrock monitoring well from the west end of Site 1, well 1GW09, responded to both the bedrock pumping test and the variation in river levels. The magnitude of the drawdown observed in that well at the start of the bedrock pumping stage of the test was less than one third of a foot. This weak response does not necessarily mean that there is low bedrock aquifer transmissivity between the extraction wells and well 1GW09. It is more likely that the water-level response to pumping was inhibited by a good hydraulic connection with the river, which may serve as a hydrologic boundary in the upper bedrock. Indeed, the river-level fluctuations are reflected in the record of 1GW09 with almost undiminished magnitude.

Well 1GW36, located in the middle of Site 1, showed a relatively strong response to the cessation of pumping at the start of the test and the onset of pumping in the bedrock pumping stage. This well also shows the imprint of fluctuations that were occurring in the river levels. Apparently, this well is closely connected to one or more of the bedrock extraction wells, and also has a fairly good connection to the river.

Well 1GW04 is the second bedrock monitoring well from the east end of Site 1. It showed a subdued response to both the bedrock pumping test and the river fluctuations. Its response during the recovery stage is reminiscent of well 1GW37, which is completed in the alluvium directly above it.

At the east end of site 1, well 1GW14 showed a rather peculiar record of water-level fluctuations. It responded strongly to the shutdown and restart of the bedrock extraction wells, but the record has no apparent relationship to the river levels. Prior to the start of the test, and during the recovery period, the water level in well 1GW14 showed a sharply variable periodic response with a frequency of one cycle per day. The source of this cyclic fluctuation is unknown, but is appears to have ceased during the bedrock pumping stage of the test.

4.3.2.2 Alluvial Extraction Wells

The pressure transducers in the alluvial extraction wells were not intended for use in data collection under non-pumping conditions. Their purpose is to accurately sense the water levels in the extraction wells when the pumps are in operation, as part of the pumping rate control loop. Nonetheless, many of them did function effectively in gathering water-level data during the bedrock pumping test. The water-level records collected by these permanent transducers are shown in figures 4-5 through 4-9.

Figure 4-5 shows the water-level records for alluvial extraction wells 1EW01 through 1EW07, on the east side of Site 1. The record from well 1EW01 was not collected because the rise in water levels over-pressurized the transducer, which is designed to indicate water levels with the pump in operation. In the six records that were recorded for these wells, the primary item of interest is the relatively weak responses to the startup of the bedrock wells during the bedrock pumping stage of the test. The magnitudes of the responses in wells 1EW02 through 1EW07 were generally less than one or two tenths of a foot. Note that water levels dropped sharply in all of the alluvial extractions wells at the end of the bedrock pumping test because the alluvial extraction system was restarted at that time.

Figure 4-6 shows the responses of the next seven alluvial extraction wells to the west. The only wells showing substantial responses to bedrock pumping were wells 1EW10, 1EW11, and 1EW14. None of these responses were greater than half a foot. The greatest response was seen in the westernmost well of the group, well 1EW14.

Figure 4-7 shows the water-level records from alluvial extraction wells 1EW15 through 1EW21. These wells are located in the western half of Site 1. With the exception of well 1EW21, in which the transducer was over-pressurized, all wells showed responses to bedrock pumping. The largest responses were seen in wells 1EW17 through 1EW20, which showed rapid drawdowns in the range of 2 to 4 feet at the start of bedrock pumping. It appears that the alluvial and bedrock aquifers are fairly well connected in that portion of Site 1.

Figure 4-8 shows alluvial water-level records in extraction wells 1EW22 through 1EW27. These are the six westernmost alluvial extraction wells at Site 1. The response to bedrock pumping in these wells declined from a maximum of about 1foot at well 1EW22 to no observable response in wells 1EW26 and 1EW27 at the west end of the site. The more westerly wells in this group followed the fluctuations in river levels rather closely, but did not respond strongly to bedrock pumping.

Figure 4-9 shows the water-level records from the three alluvial extraction wells at Site 10. They showed very little change in water level over the two-week period of the test. Specifically, there was no observed response to bedrock pumping. There was a slight tendency for general decline in groundwater levels. Wells 10EW35 and 10EW36 also showed slight increases on July 8, probably resulting from rainfall.

4.4 Potentiometric Surface Mapping

4.4.1 Maps for June 26, 2001

The comprehensive round of synoptic water-level measurements taken on June 26, 2001 and displayed in Table 4-1 served two purposes. First, it was the regular monthly monitoring round for June, and was used in the usual way to evaluate the hydraulic performance of the groundwater extraction systems. Second, it served as a baseline condition at the start of the bedrock test that was compared with the second synoptic monitoring round to evaluate recovery in both aquifers when the extraction wells were shut off.

The average pumping rates of the extraction wells in the 14 hours prior to system shutdown are listed in Table 4-2. The three extraction wells at Site 10 had been turned off for several days during the investigation of a fuel spill in the area. The alluvial and bedrock extraction wells at Site 1 were operating at typical pumping rates.

Figure 4-10 shows the potentiometric surface map and the measured water levels in the alluvial aquifer measured on the morning of June 26, 2001, just prior to system shutdown. Although the maps shows localized zones of drawdown around the alluvial extraction wells at Site 1, several of the alluvial monitoring wells adjacent to the river had water levels that were higher than the river level. The conditions of June 26 were atypical because the preceding few days were times of significant rainfall and high river levels (see Figure 4-1). The river level had dropped about 2 feet in the 48 hours prior to the morning of June 26, but the groundwater levels could not respond that quickly. Therefore, even though the Site-1 extraction wells were capturing a substantial portion of the groundwater flowing toward the river, there was a temporary period of northward flow near the northern perimeter of Site 1.

Figure 4-10 also shows the location of the leaky storm sewer line at Site 10 and gives the invert elevations at the manholes. Comparison with the potentiometric surface at Site 10 shows that the sewer line was below the water table on June 26, when the Site 10 alluvial extraction wells were not pumping. The location of the sewer line in the northeast portion of Site 10 corresponds to a depression of the water table that is at least partially caused by groundwater inflow to the sewer under natural groundwater flow conditions (i.e., unpumped).

Figure 4-11 shows the potentiometric surface and measured water levels in the bedrock aquifer for the morning of June 26, 2001, just prior to system shutdown. At Site 1, the situation in the bedrock aquifer was much like the situation in the alluvial aquifer. Although the bedrock extraction wells were producing an area of substantial drawdown and were intercepting much of the flow toward the river, water levels in at least one of the bedrock monitoring wells near the river bank (i.e., 1GW04) was higher than the river level. A notable exception was bedrock well 1GW14, which is strongly affected by drawdown produced by the bedrock extraction wells.

The bedrock potentiometric surface map at Site 10 shows generally eastward flow with a strong hydraulic gradient between wells 10GW18 and 10GW20 (Figure 4-11). Flow in the bedrock aquifer appears to converge toward the area of monitoring wells 10GW20 and 10GW22. This is the same area in which water levels were depressed in the alluvial aquifer around the leaking storm sewer. However, a very important observation from these maps is that the vertical direction of flow in this area was downward from the alluvium into the bedrock. Therefore, the low bedrock water levels in this area cannot be attributed to the leaking storm sewer. They must be caused by a zone of enhanced groundwater flow in the bedrock.

4.4.2 Maps for July 2, 2001

Figure 4-12 shows the potentiometric surface and the water levels measured in the alluvial aquifer on July 2, 2001, at the end of the recovery stage of the bedrock test and before the start of the bedrock pumping stage. In addition to the water levels in the monitoring wells, the figure also lists the water levels measured in the Site-1 alluvial extraction wells, which were not being pumped. Inclusion of the 27 alluvial extraction wells permits more detailed mapping of the potentiometric surface at Site 1. The potentiometric surface shown in Figure 4-12 is the best available depiction of natural, non-pumping, alluvial groundwater flow patterns in the study area.

At Site 10, the potentiometric surface again shows a depressed water table along the leaky storm sewer line. The water table, although lower than on June 26, is still higher than the storm sewer inverts, indicating the potential for groundwater infiltration into the sewer. On July 2, a measurement of the flow in the sewer line was made by plugging the inflow line to the manhole with an invert of 660.85 feet and installing a v-notch weir in the next manhole downstream (invert = 658.49 feet). A flow rate of approximately 8 gpm was measured in the downstream manhole. This flow is attributed to groundwater infiltration into the sewer line between the two manholes.

Figure 4-13 shows the water levels and potentiometric surface in the bedrock aquifer at the end of the recovery stage of the test. Because of the large number of monitoring wells used, this map is considered the best available depiction of natural flow in the bedrock in the study area. Again, the bedrock groundwater levels at the eastern end of Site 10 are lower than the alluvial water levels. This confirms that the trough in the bedrock potentiometric surface in the vicinity of wells 10GW20 and 10GW22 in not caused by the leaky storm sewer in the alluvium.

4.4.3 Maps for July 10, 2001

Figure 4-14 shows the potentiometric surface and groundwater levels measured in the alluvial aquifer on July 10, 2001, at the end of the bedrock pumping stage of the test and before the extraction system was returned to normal operation. The figure also shows the estimated boundary of the hydraulic capture zone in the alluvial aquifer produced by pumping the bedrock extraction wells alone. Evaluation of the alluvial capture that could be achieved by bedrock pumping alone was one of the specific objectives of the bedrock pumping test. As the figure shows, alluvial capture was achieved only within a relatively narrow segment of the western end of the Site 1. This appears to be an area of relatively good hydraulic interconnection between the alluvium and the bedrock. Over most of the rest of Site 1, bedrock pumping had little apparent effect on the alluvial aquifer. The alluvial potentiometric surface map for July 10 again benefited from the use of the alluvial extraction wells as monitoring points.

Figure 4-15 shows the potentiometric surface and groundwater levels measured in the bedrock aquifer at the end of the bedrock pumping stage of the test. The potentiometric surface very clearly shows a connected zone of drawdown encompassing the line of bedrock extraction wells. Hydraulic migration control was complete along this line, as it typically has been during normal operation of the Site 1 extraction system. The average pumping rates of the seven bedrock extraction wells during the bedrock test are listed in Table 4-3. The total rate of bedrock pumping averaged 82.6 gpm. It is notable that even with maximized pumping of the bedrock extraction wells, monitoring well 1GW12, at the west end of Site 1, still had a water level higher than the river level at the upstream staff gauge.

4.5 Drawdown Maps

The drawdown created in the alluvial and bedrock aquifers during the seven-day bedrock pumping segment of the test were calculated at each monitoring well by subtracting the water level measured on July 10 from the level measured on July 2.

Figure 4-16 shows a contour map of the calculated drawdown in the alluvial aquifer as a result of the bedrock pumping stage of the test. Areas of positive drawdown are indicated by the blue contour lines. Positive drawdown occurs when the water levels are lower at the end of the bedrock pumping stage than they were before pumping started. That is the anticipated effect of pumping. The area of most substantial alluvial drawdown was found in the western part of Site 1. This is the same area where hydraulic capture was achieved in the alluvium during bedrock pumping. The highest drawdown value, 4.88 feet, occurred at alluvial extraction well 1EW20. Drawdown values of more than 2 feet were recorded in the next well to the west, 1EW21, and as far east as well 1EW17. This appears to indicate a zone in which the alluvial and bedrock aquifers have a relatively good hydraulic connection.

In some areas, the figure shows zero or negative drawdown contours. These are areas where the water levels increased or stayed the same during the bedrock pumping stage of the test. Negative drawdown values were calculated near the North Branch Potomac River because the river level rose slightly during the bedrock pumping stage of the test. There were also some negative drawdown values in the alluvium at Site 1. The rise in water levels is believed to have been caused by rain that fell at ABL during the test (see Figure 4-1).

Figure 4-17 shows the map of drawdown in the bedrock aquifer during the bedrock pumping stage of the test. Drawdown values were not calculated for the bedrock extraction wells themselves because the measurements would have included well losses, and would not be indicative of actual water levels in the aquifer. The highest drawdown detected in a monitoring well was a value of 9.64 feet in well 1GW15. Other relatively high values were measured in bedrock wells immediately south of the area of bedrock extraction. In addition, a surprisingly high drawdown of 5.66 feet was detected in well 1GW14, adjacent to the North Branch Potomac River. This amount of drawdown is unexpected so near the river because the river is expected to act as a hydrologic boundary that would prevent significant change in water level in the adjacent wells by providing significant recharge.

A major objective of the bedrock test was to evaluate the hydraulic interactions in the bedrock between Site 1 and Site 10. Figure 4-17 shows that drawdown created by pumping the bedrock extraction wells propagated through the bedrock toward the eastern side of Site 10, where drawdown values of more then 0.5 ft were measured. Farther to the west, drawdown from the Site 1 bedrock extraction wells decreased more rapidly with distance south of Site 1. This suggests a difference in the flow characteristics of the rock on the eastern side of sites 1 and 10. The area on the eastern side of Site 10, where higher drawdown was observed, is also the area that showed convergence of flow toward a trough in the potentiometric surface maps. This evidence suggests a band of relatively high hydraulic conductivity in the bedrock leading from the eastern side of Site 10 toward the eastern side of Site 1. Water levels in this band are affected by pumping from the bedrock extraction wells. When there is no pumping (i.e. on June 26), the groundwater levels in this permeable zone indicate groundwater flow toward the river.

4.6 Summary

The results of the bedrock test provided the following answers to the questions posed by the test objectives:

- Satisfactory hydraulic containment of contaminated groundwater in the alluvial aquifer at Site 1 cannot be attained by pumping the bedrock extraction wells alone. The bedrock pumping test produced hydraulic capture only in a relatively narrow zone on the western side of Site 1.

- The downward vertical gradients at Site 10 occur naturally, and are most severe on the east side of Site 10. Drawdown propagates through the bedrock from Site 1 toward the east side of Site 10. This increases the downward vertical gradients and the easterly convergence of bedrock flow at Site 10. However, the same phenomena are clearly present even when the Site 1 extraction system is not operating.

- Satisfactory target data sets for steady-state groundwater model calibration are provided by the natural potentiometric surface maps and the groundwater levels measured on July 2, at the end of the recovery period. The drawdown measurements obtained by comparing the water levels on July 10 with those of July 2 are suitable for calibrating the model for bedrock pumping conditions.

In addition, the potentiometric surface mapping based on measurements taken during the bedrock test show that the leaky storm sewer at Site 10 abstracts groundwater from the alluvial aquifer during periods of high groundwater levels. However, the storm sewer is not responsible for the northeasterly convergence of groundwater flow in the bedrock aquifer at Site 10.

Table 4-1

Results of Synoptic Water Level Measurements

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

	June 26, 2001		July 2, 2001		July 10, 2001	
Well	Water level	Measurement Time	Water level	Measurement Time	Water level	Measurement Time
1EW1	648.7	859	650.34	1029	650.4	702
1EW2	646.4	903	650.79	1030	650.71	703
1EW3	649.83	910	650.83	1033	650.89	706
1EW4	649.8	913	650.95	1035	650.94	711
1EW5	649.43	915	651.07	1037	651.02	655
1EW6	649.98	702	651.16	1113	651.06	651
1EW7	648.83	705	651.41	1112	651.28	649
1EW8	650.31	707	651.82	1111	651.57	648
1EW9	650.19	710	651.82	1110	651.79	647
1EW10	647.95	712	652.04	1109	651.57	646
1EW11	646.35	714	651.99	1108	651.51	645
1EW12	649.59	716	651.79	1107	651.79	644
1EW13	648.48	718	651.11	1106	651.06	643
1EW14	646.73	720	650.55	1105	650.1	642
1EW15	646.97	722	651.07	1104	649.73	641
1EW16	648.04	724	652.04	1103	650.24	639
1EW17	647.42	726	651.9	1102	648.14	638
1EW18	646.87	728	651.58	1100	649.07	637
1EW19	645.38	730	651.42	1058	647.97	636
1EW20	648.3	732	652.78	1055	647.9	635
1EW21	648.06	756	651.09	950	648.95	756
1EW22	648.74	754	650.18	949	649.14	800
1EW23	648.32	742	649.42	945	649.03	812
1EW24	647.43	740	649.59	944	649.35	811
1EW25	648.09	739	649.23	943	649.39	809
1EW26	648.33	737	648.81	941	649.29	808
1EW27	648.07	733	649.27	940	649.63	805
1EW28	640.49	748	650.75	957	615.21	749
1EW29	651.11	735	654.37	1124	640.85	633
1EW30	594.86	738	653.85	1123	625.99	631
1EW31	642.11	741	652.07	1122	633.2	629
1EW32	651.23	743	652.74	1120	637.9	627
1EW33	639.53	700	649.65	1118	634.78	652
1EW34	643.65	919	649.31	1040	641.6	712
1EW35	648.78	735	648.67	1130	649.11	806
1GW1	650.37	900	649.88	1151	650.26	831
1GW2	648.93	730	648.86	937	649.27	803
1GW3	649.14	714	649.66	1005	649.02	733
1GW4	649.43	719	649.67	1009	649.24	738
1GW5	649.64	917	650.43	1022	650.47	657
1GW6	663.99	1126	663.31	1202	663.28	848
1GW7	664.28	1128	664.16	1325	664.29	858
1GW8	648.47	905	650.46	1031	648.41	705
1GW9	648.72	712	648.73	1004	648.82	715
1GW10	651.58	941	655.92	1300	648.99	844

Table 4-1
Results of Synoptic Water Level Measurements
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Well	June 26, 2001		July 2, 2001		July 10, 2001	
	Water level	Measurement Time	Water level	Measurement Time	Water level	Measurement Time
1GW11	658.21	942	657.8	1301	655.92	845
1GW12	649.25	731	649.13	938	649.5	804
1GW13	649.5	711	650.84	1003	647.74	730
1GW14	644.96	918	648.32	1028	642.66	659
1GW15	651.51	948	654.5	1316	644.86	842
1GW20	647.57	927	651.49	1018	645.15	725
1GW21	645.36	925	649.9	1020	643.59	821
1GW22	645.17	928	650.22	1038	642.99	715
1GW24	650.18	921	651.08	1039	651.07	709
1GW25	650.11	924	651	1040	651.02	708
1GW27	649.36	752	650.88	952	648.35	754
1GW28	649.29	750	650.78	959	648.28	746
1GW29	650.26	758	652	1000	648.44	744
1GW30	650.1	747	651.39	956	649	747
1GW31	649.35	745	650.76	954	648.91	751
1GW32	653.46	905	653.53	1016	653.08	726
1GW33	651.71	837	650.38	933	651.11	826
1GW34	649.01	756	649.76	1053	648.87	621
1GW35	648.84	753	649.66	1051	649.8	623
1GW36	648.83	751	650.13	1050	647.76	624
1GW37	649.77	748	650.23	1048	649.78	625
1GW38	649.67	920	650.54	1026	650.54	701
1GW39	648.85	729	648.86	936	649.26	801
GGW-1	654.15	935	653.26	1201	653.75	833
GGW-2	653.83	937	653.09	1202	653.57	834
GGW-3	665.67	1102	664.72	1209	664.53	949
GGW-4	665.02	1104	664.48	1210	664.29	950
2-GW3	658.69	1026	658.08	1313	657.75	955
2-GW6	654.55	1030	655.04	1315	653.11	957
2-GW7	653.32	1014	653.51	1324	652.19	1000
GGW-11	665.32	1111	664.38	1130	664.16	851
GGW-12	666.32	1114	664.98	1132	664.79	853
GGW-13	664.7	1109	663.9	1128	663.76	854
10GW01	663.9	1123	663.39	1121	663.39	921
10GW02	663.82	1122	663.35	1120	663.35	922
10GW03	663.86	1120	663.41	1117	663.36	931
10GW04	663.88	1124	663.39	1123	663.32	924
10GW05	662.01	1109	661.65	1319	661.34	934
10GW06	663.9	1111	663.4	1115	663.32	929
10GW07	662.49	1039	662.19	1150	662.14	909
10GW08	664.41	1118	663.67	1125	663.56	926
10GW09	663.88	1114	663.39	1113	663.37	928
10GW10	663.83	1113	663.38	1111	663.34	930
10GW12	663.53	1025	662.91	1204	662.45	936
10GW13	661.65	1108	661.38	1158	661.4	913

Table 4-1
Results of Synoptic Water Level Measuements
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Well	June 26, 2001		July 2, 2001		July 10, 2001	
	Water level	Measurement Time	Water level	Measurement Time	Water level	Measurement Time
10GW14	663.81	1029	663.42	1138	663.56	901
10GW15	663.68	1030	663.39	1140	663.47	902
10GW16	662.51	1040	662.08	1058	661.88	941
10GW17	663.32	1046	662.64	1055	662.27	940
10GW18	663.79	1032	663.54	1141	663.33	903
10GW19	663.86	1112	663.35	1108	663.27	935
10GW20	661.01	1036	660.71	1144	660.12	906
10GW21	661.99	1041	660.73	1154	661.72	911
10GW22	660.92	1042	660.8	1155	660.13	912
10GW23	663.53	1035	663.15	1146	663.14	907
10GW24	663.28	1037	661.94	1148	662.93	908
10GW25	662.14	1042	661.59	1100	661.33	943
10GW26	663.43	1023	662.75	1206	662.38	937
10GW27	658.21	1033	658.13	1105	656.92	947
10EW35	660.83	1034	660.45	1143	660.41	904
10EW05	663.34	1100	662.9	1342	663.01	1015
10EW37	659.21	1040	659.04	1151	659.01	910
PWA-1	663.82	1119	663.45	1135	663.51	918
PWA-2	663.86	1117	663.5	1154	663.55	919
GGW05	662.2	1021	662.36	1308	661.26	953
GGW06	660.88	1023	660.11	1307	659.97	954
2GW05	662.1	1035	661.44	1102	660.87	946
Upstream Staff Gauge	648.92	700	648.8	921	649.23	829
Downstream Staff Gauge	648.35	912	648.28	1145	648.62	722

Table 4-2

Extraction System Pumping Rates on June 26, 2001 Before Bedrock Test

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

Well	Average* Flow (gpm)	Well	Average* Flow (gpm)
1EW01	2.7	1EW20	1.5
1EW02	6.7	1EW21	1.2
1EW03	0.0	1EW22	0.4
1EW04	2.5	1EW23	4.1
1EW05	4.7	1EW24	0.8
1EW06	0.0	1EW25	0.7
1EW07	11.9	1EW26	1.6
1EW08	2.8	1EW27	2.7
1EW09	1.8	1EW28	2.9
1EW10	3.0	1EW29	1.0
1EW11	7.6	1EW30	7.8
1EW12	3.1	1EW31	8.2
1EW13	2.8	1EW32	2.1
1EW14	1.1	1EW33	8.1
1EW15	1.4	1EW34	7.5
1EW16	0.4	10EW35	0.0
1EW17	0.8	10EW36	0.0
1EW18	0.8	10EW37	0.0
1EW19	1.2	Total	105.8

* Average calculated for 14 hours prior to system shutdown.

Table 4-3

Average Extraction Well Pumping Rates During the Bedrock Pumping Test July 3 - July 10, 2001

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

Well	Average Pumping Rate (gpm)
1EW28	4.8
1EW29	12.0
1EW30	7.3
1EW31	22.3
1EW32	8.8
1EW33	16.9
1EW34	10.4
Total	**82.6**

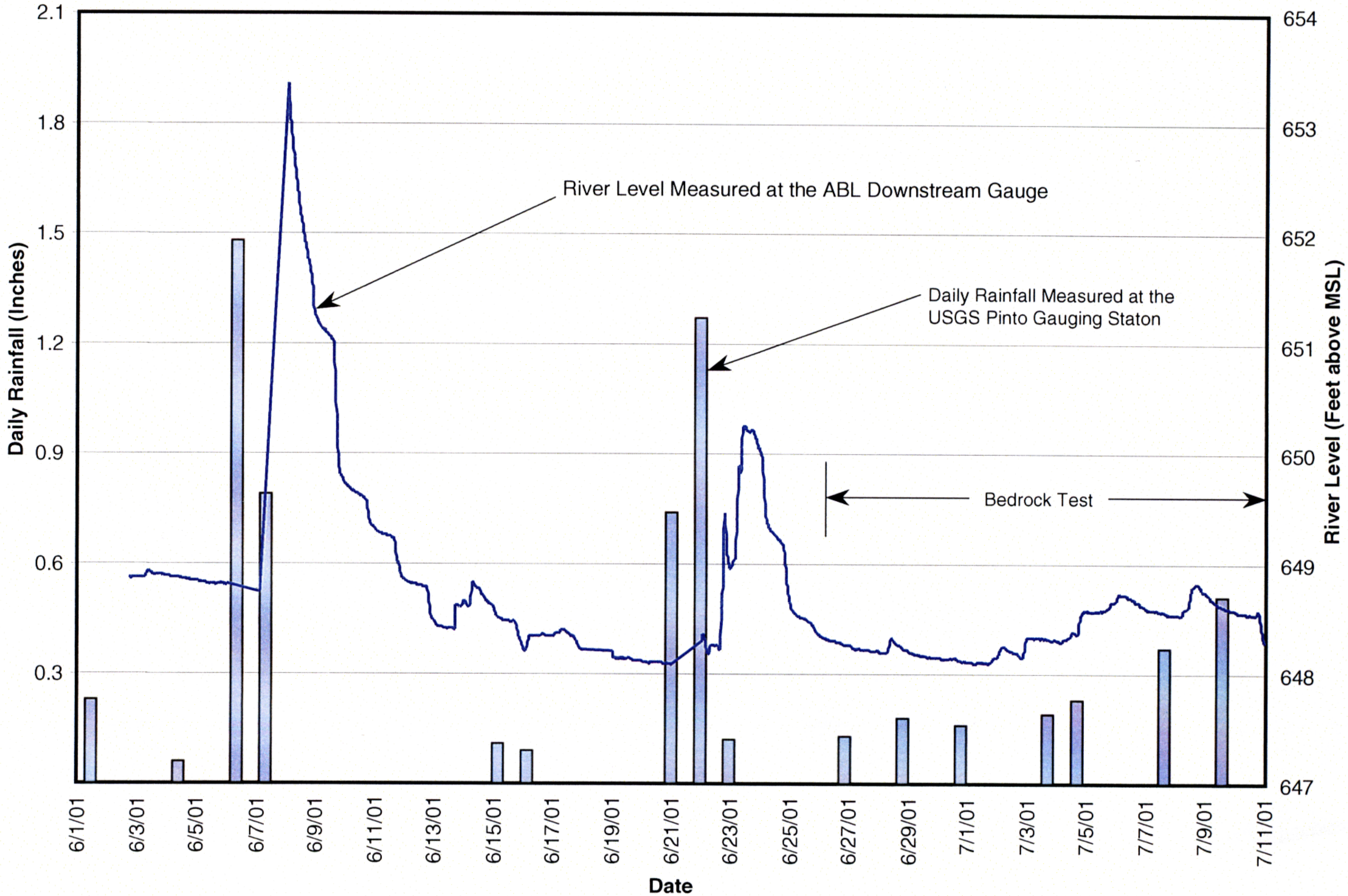

Figure 4-1
Rainfall and River Level Records for the Period June 1 to July 11, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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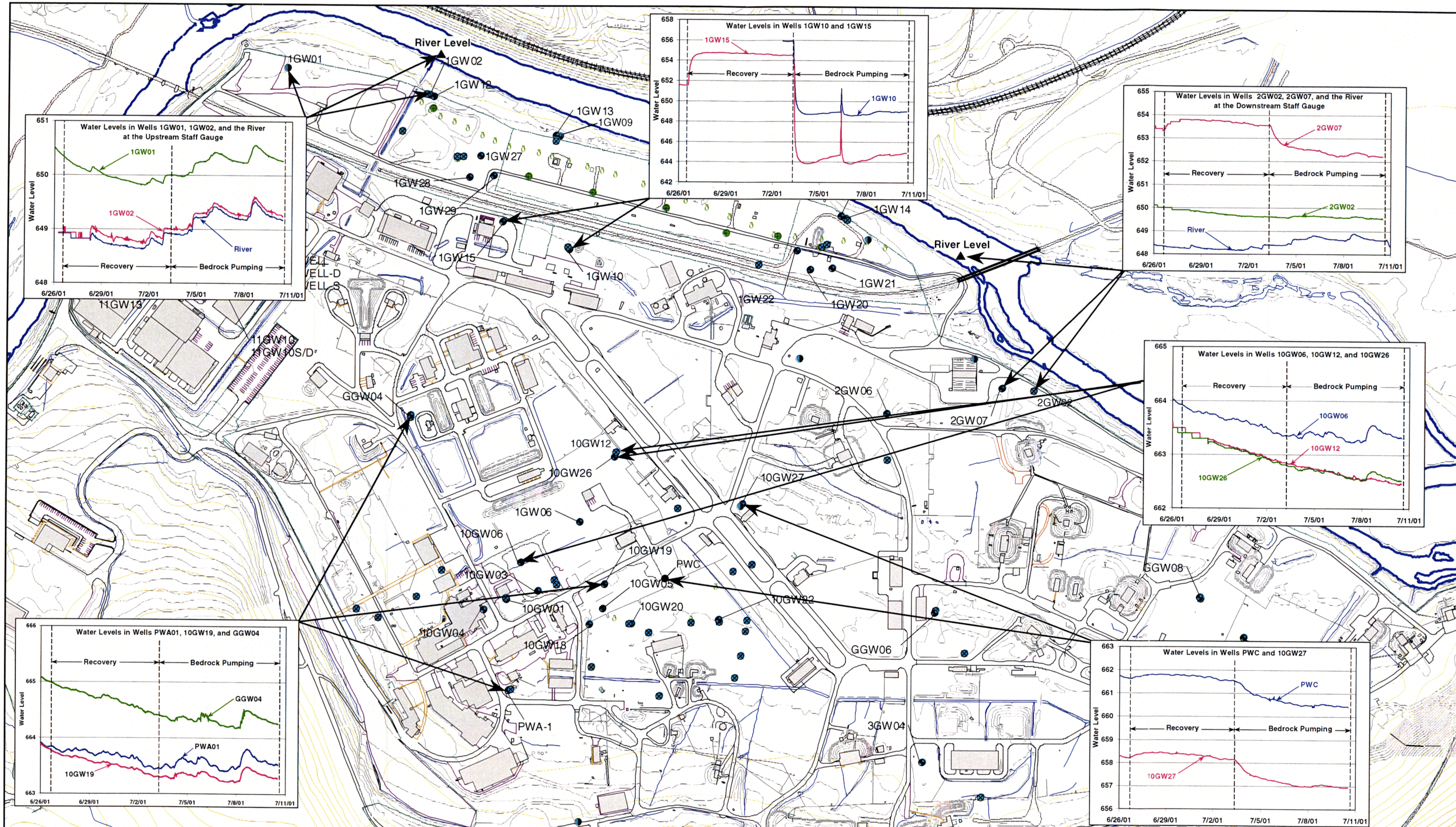

LEGEND

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Hybrid
- Monitoring Well - Alluvial
- Monitoring Well - Bedrock

N

400 0 400 800 Feet

Figure 4-2
Hydrographs Recorded by Data Loggers During the Bedrock Aquifer Test, June 26-July10, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

CH2MHILL

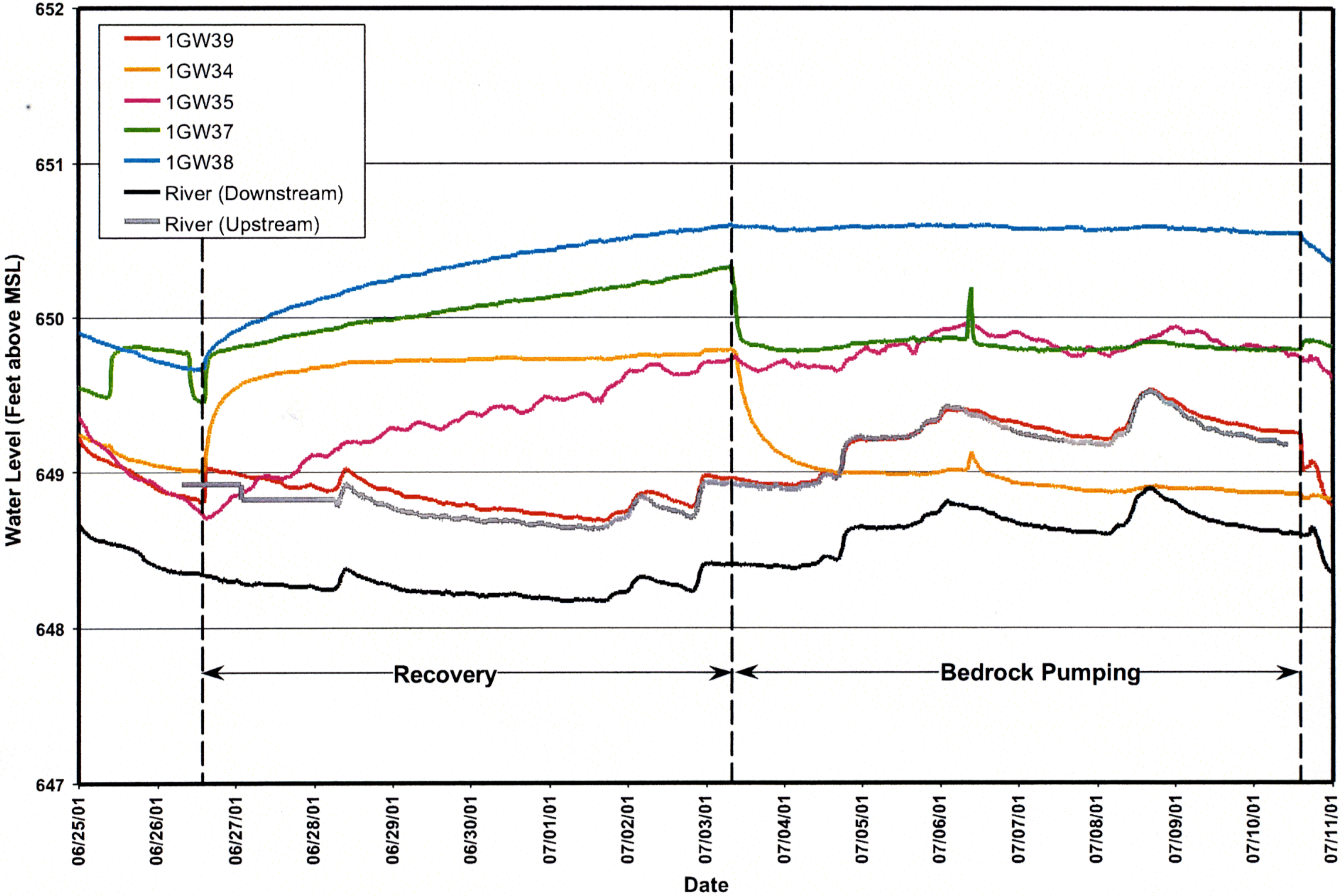

Figure 4-3
Water-Level Records from Alluvial Monitoring Wells Near the River at Site 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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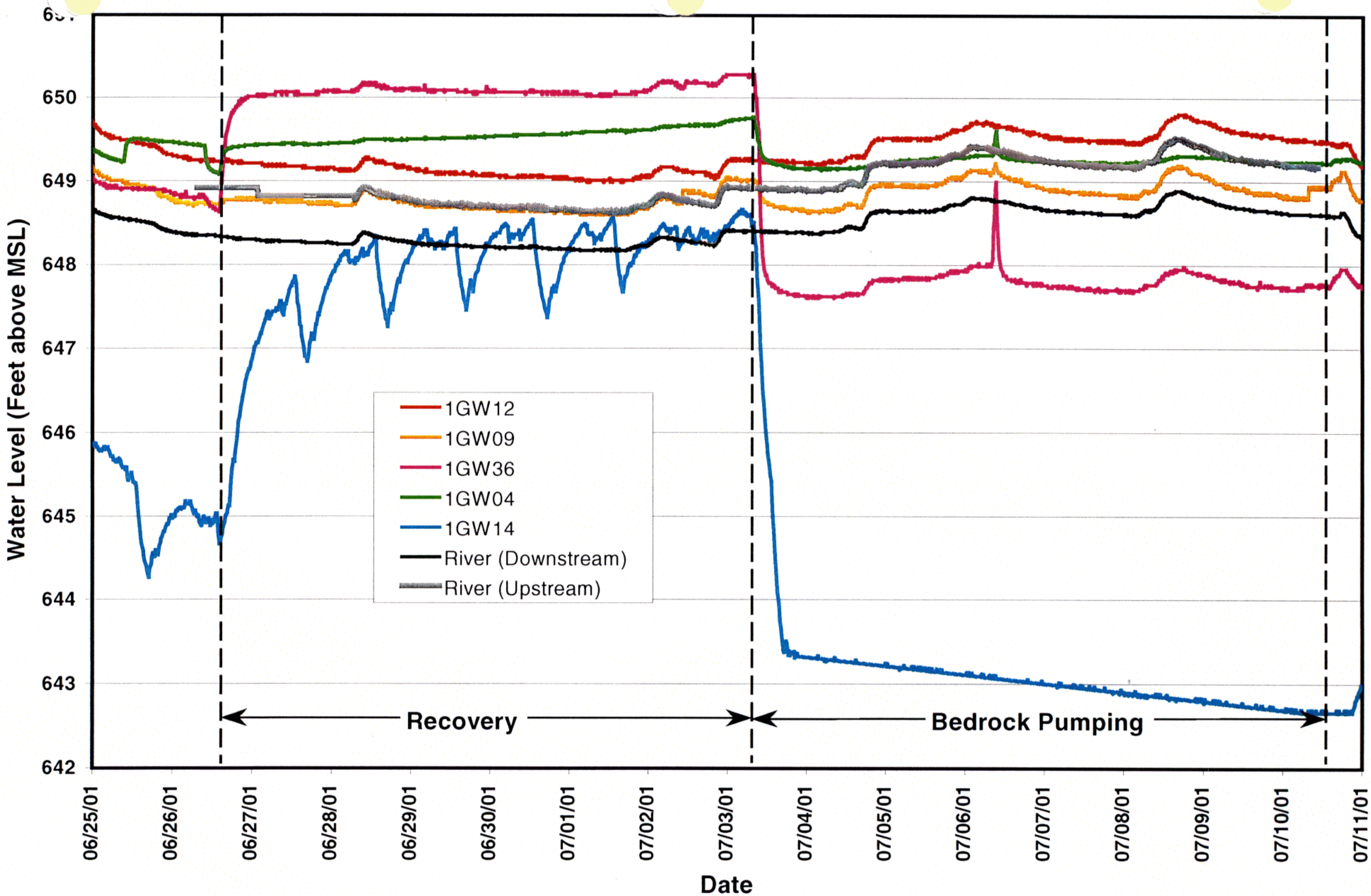

Figure 4-4
Water-Level Records from Bedrock Monitoring Wells Near the River at Site 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

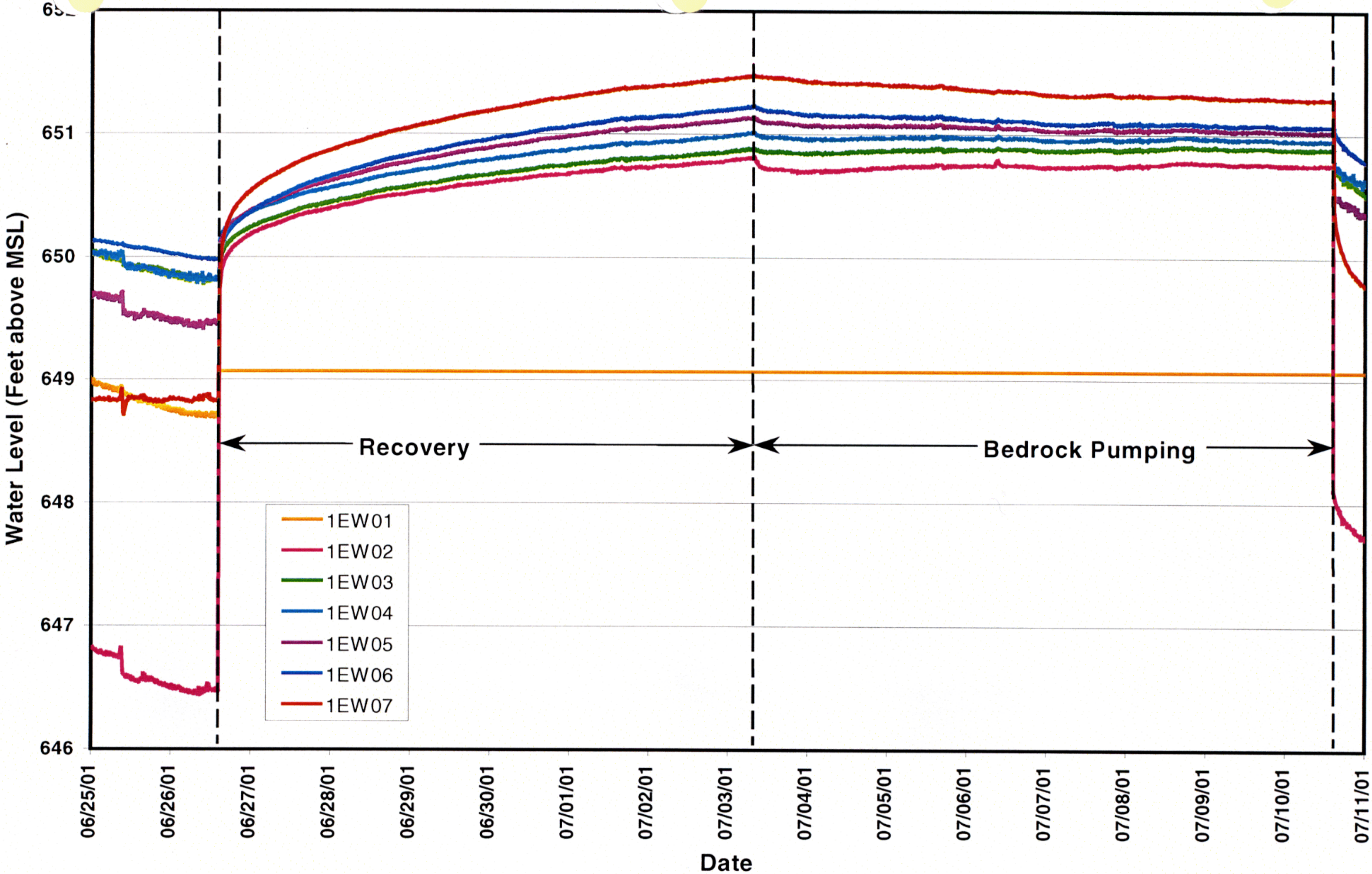

Figure 4-5
Water-Level Records from Alluvial Extraction Wells 1EW01 through 1EW07
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

CH2M HILL

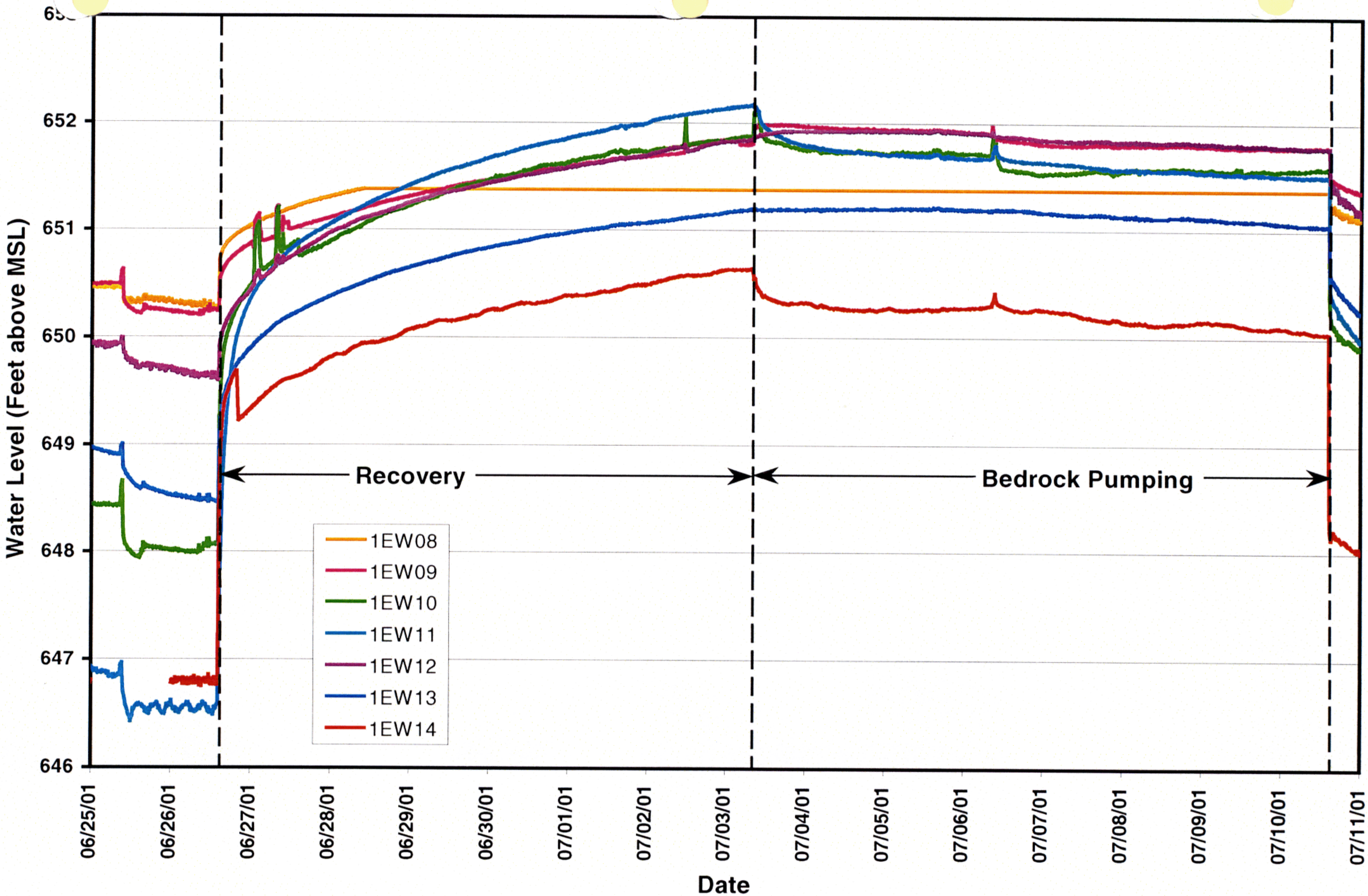

Figure 4-6
Water-Level Records from Alluvial Extraction Wells 1EW08 through 1EW14
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

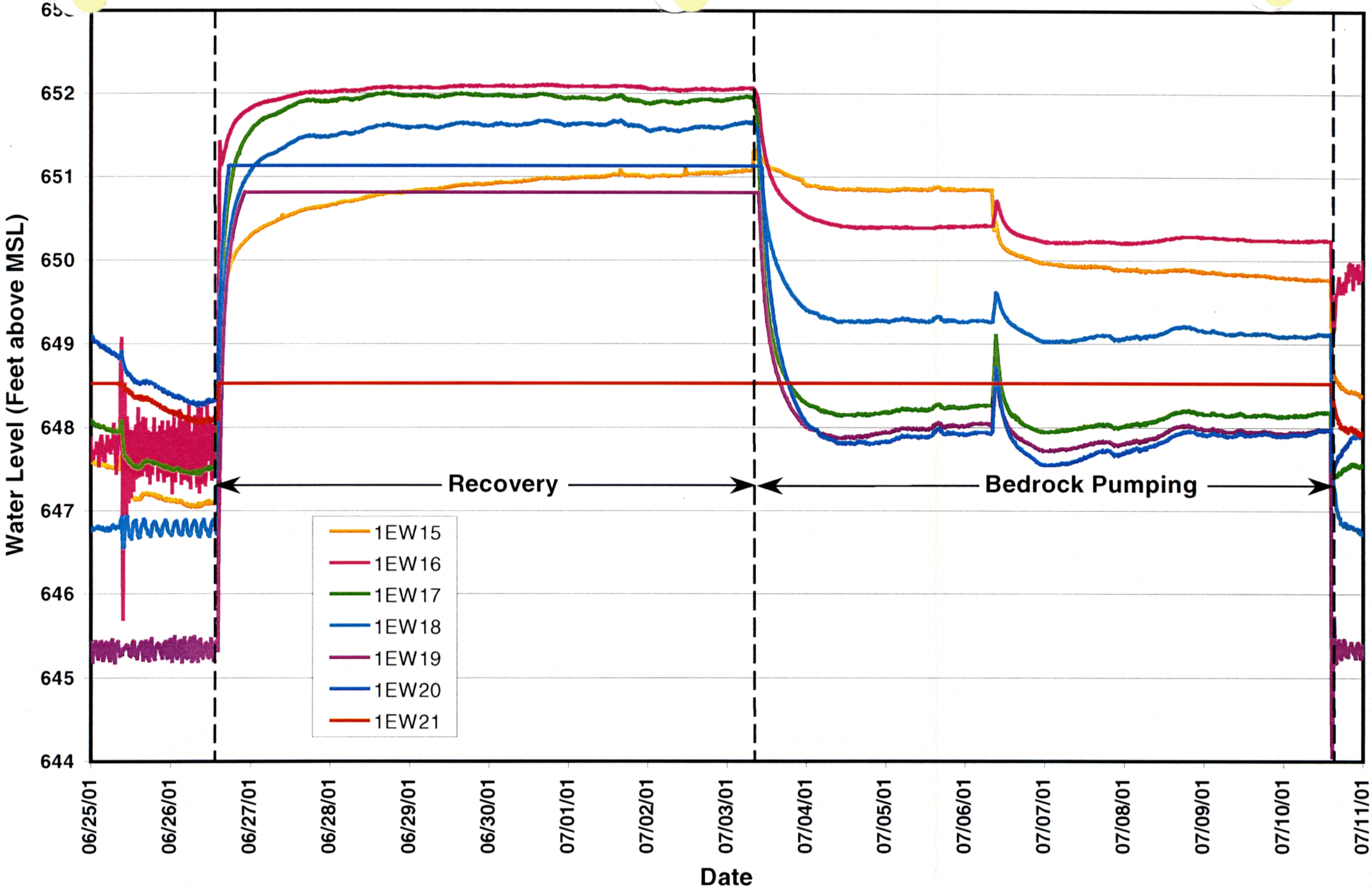

Figure 4-7
Water-Level Records from Alluvial Extraction Wells 1EW15 through 1EW21
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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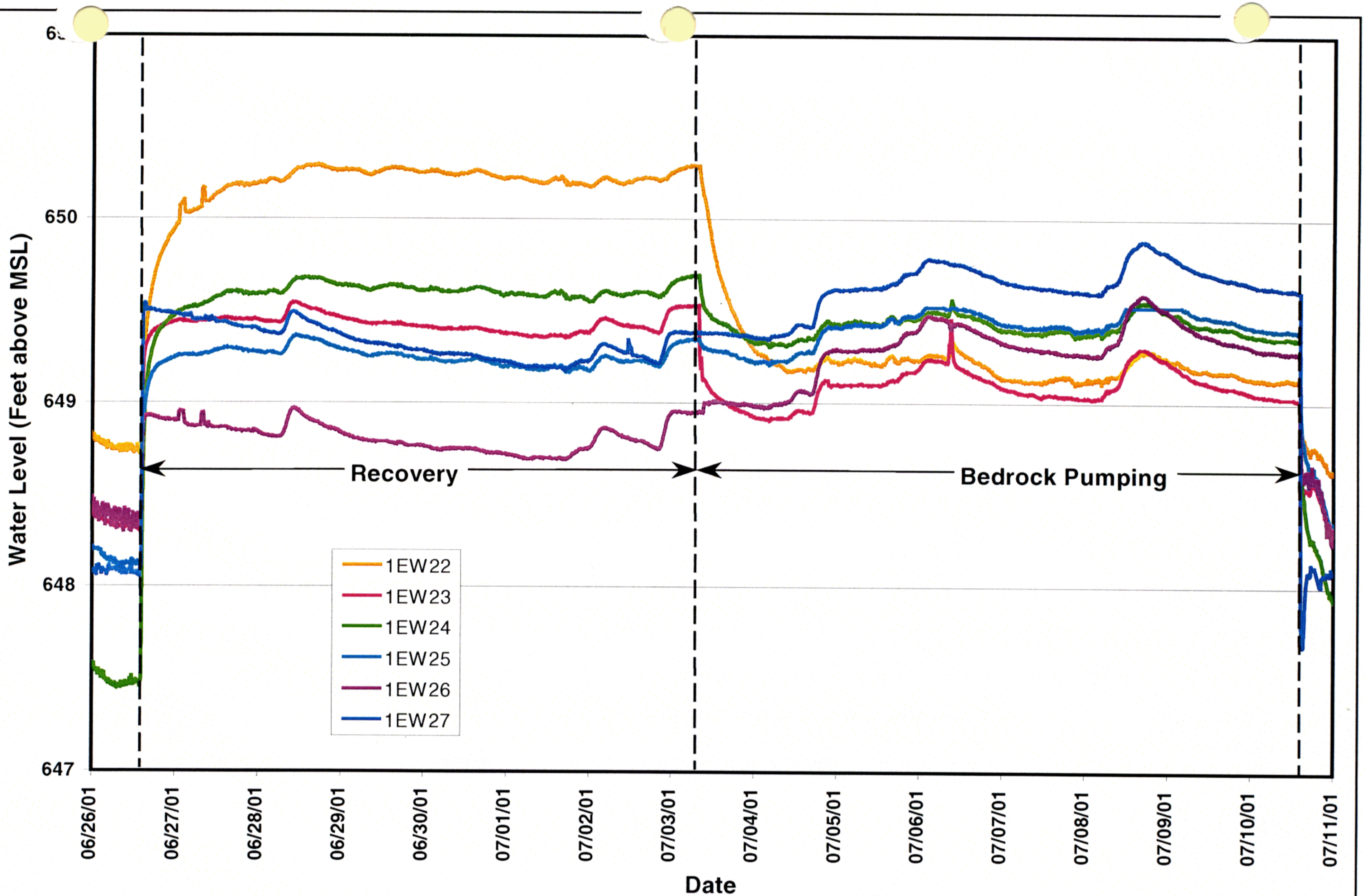

Figure 4-8
Water-Level Records from Alluvial Extraction Wells 1EW22 through 1EW27
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

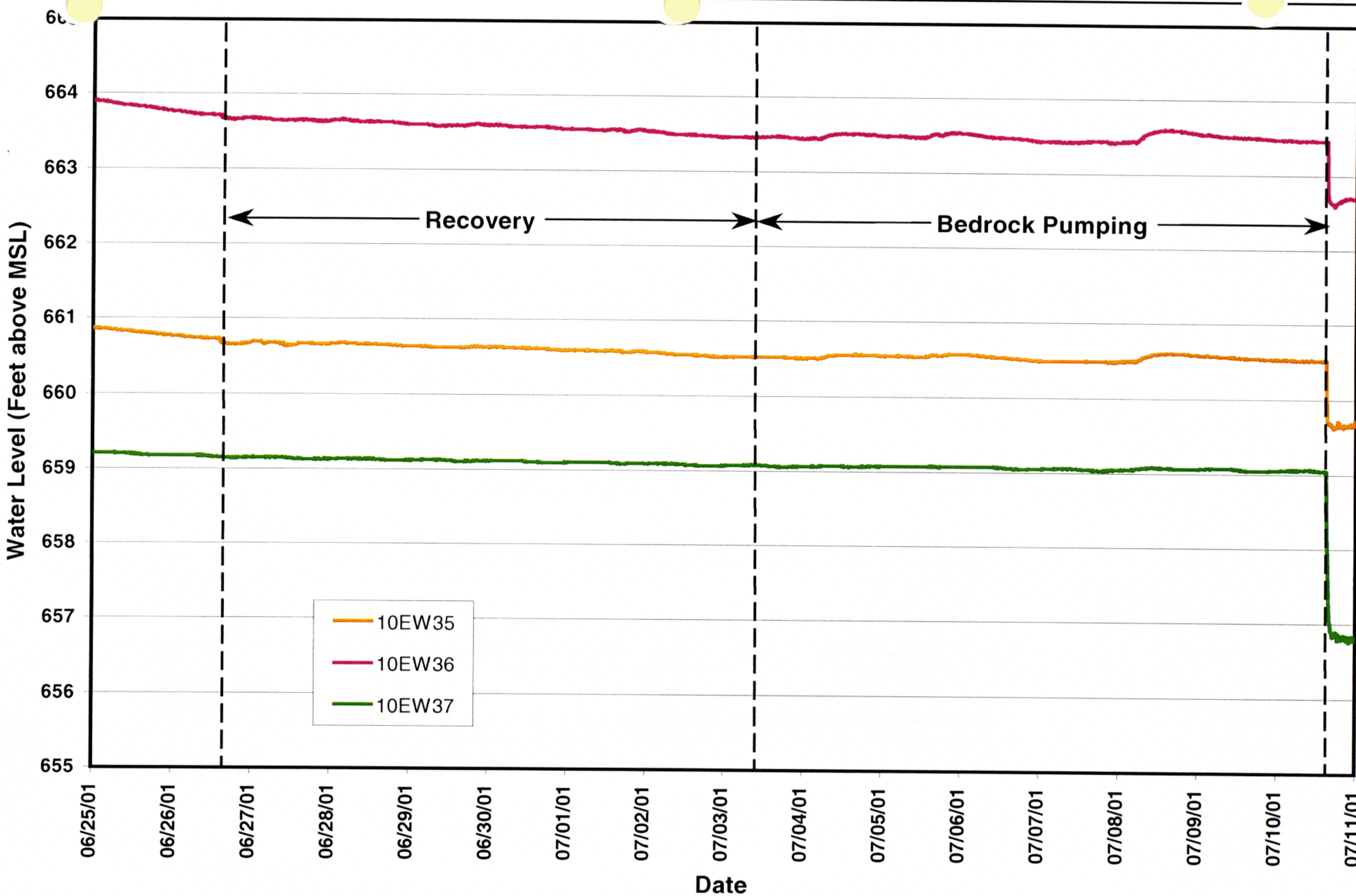

Figure 4-9
Water-Level Records from Alluvial Extraction Wells 10EW35 through 10EW37
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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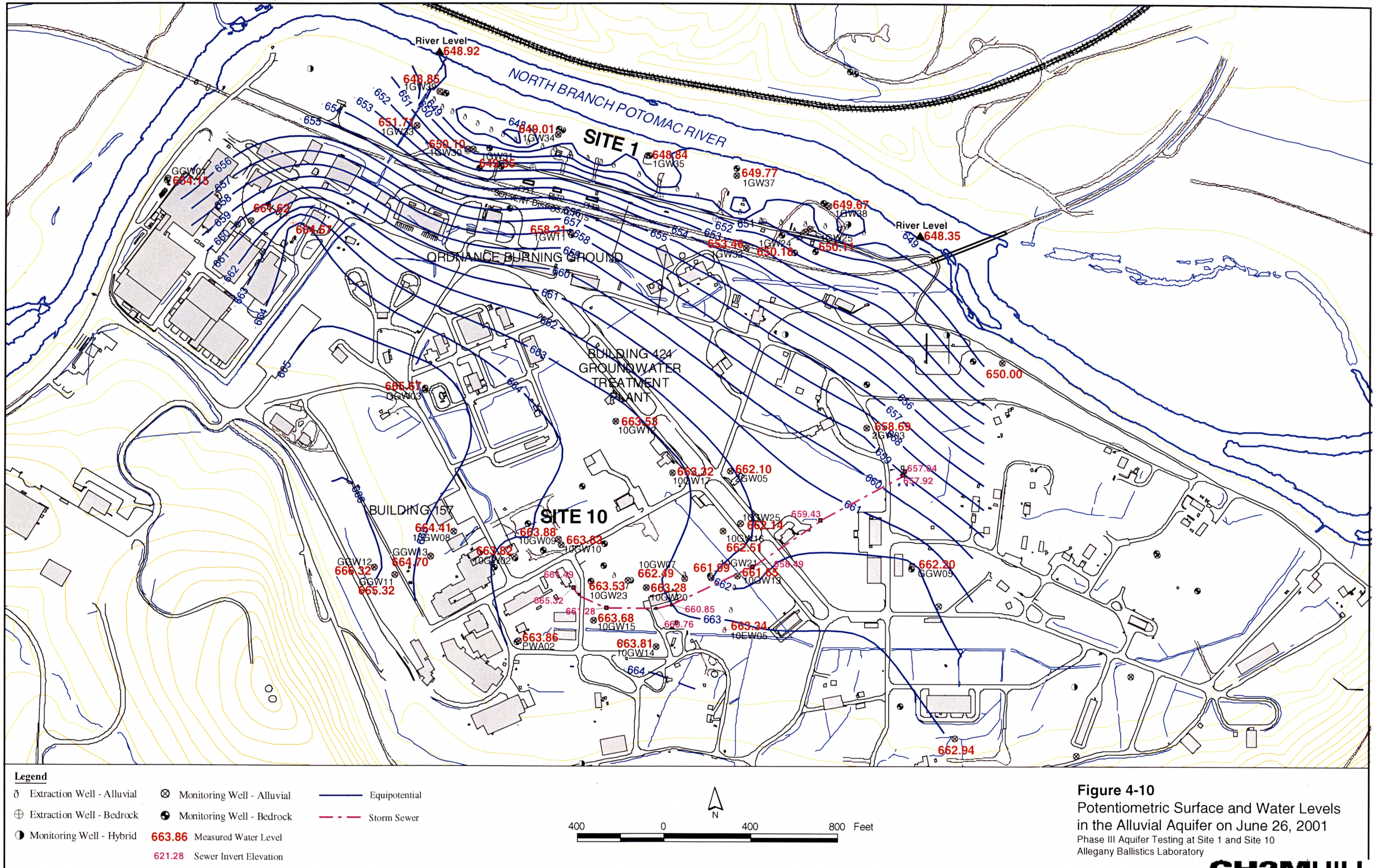

Figure 4-10
Potentiometric Surface and Water Levels in the Alluvial Aquifer on June 26, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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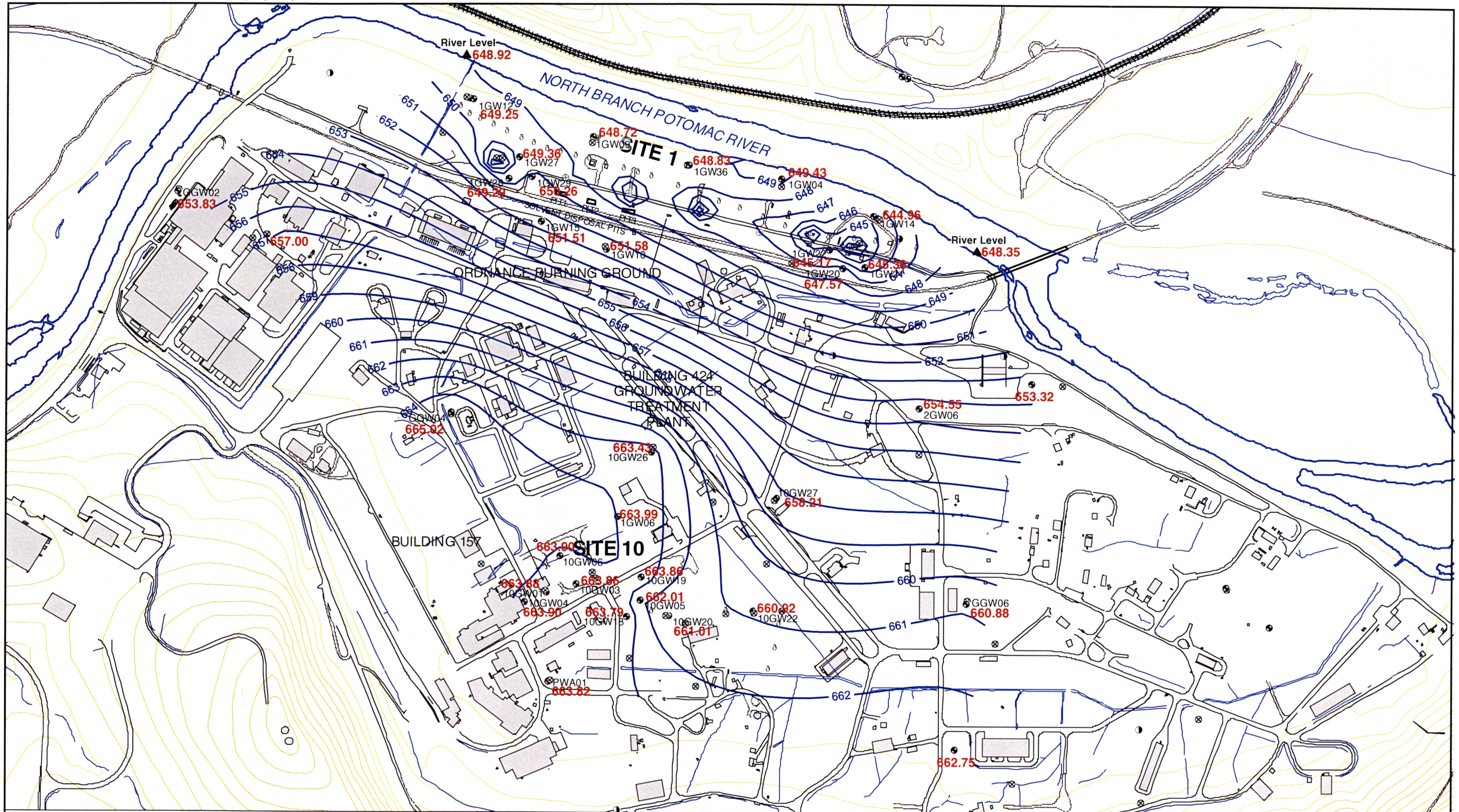

Legend

- ♁ Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ⊛ Monitoring Well - Bedrock
- 663.86 Measured Water Level
- —— Equipotential

N

400 0 400 800 Feet

Figure 4-11
Potentiometric Surface and Water Levels in Bedrock Aquifer on June 26, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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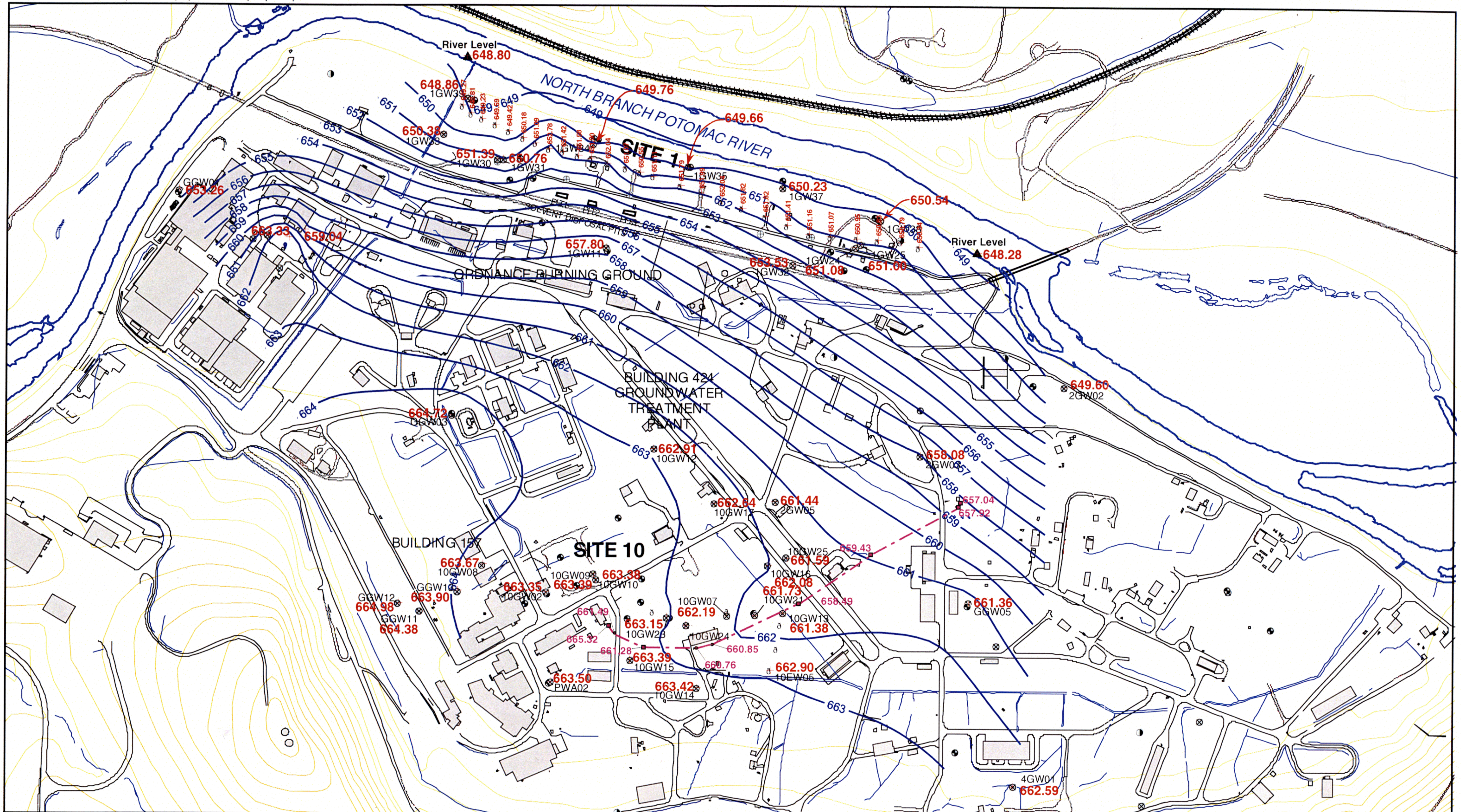

Legend

- ծ Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ● Monitoring Well - Bedrock
- 663.86 Measured Water Level
- 621.28 Sewer Invert Elevation
- Equipotential
- Storm Sewer

N

400 0 400 800 Feet

Figure 4-12
Potentiometric Surface and Water Levels in the Alluvial Aquifer on July 2, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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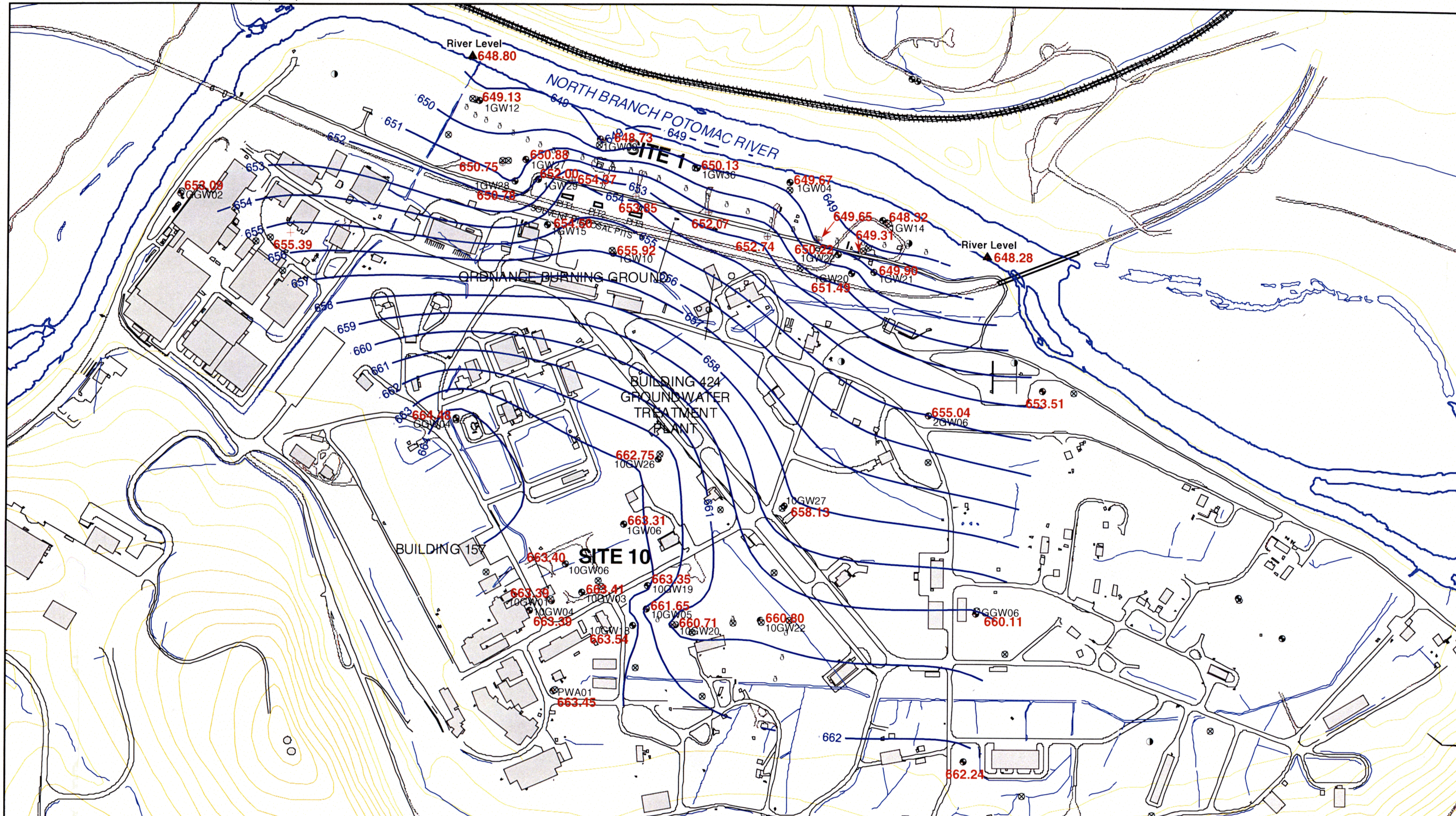

Legend

- ð Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ⊛ Monitoring Well - Bedrock
- 663.86 Measured Water Level
- —— Equipotential

N

400 0 400 800 Feet

Figure 4-13
Potentiometric Surface and Water Levels in the Bedrock Aquifer on July 2, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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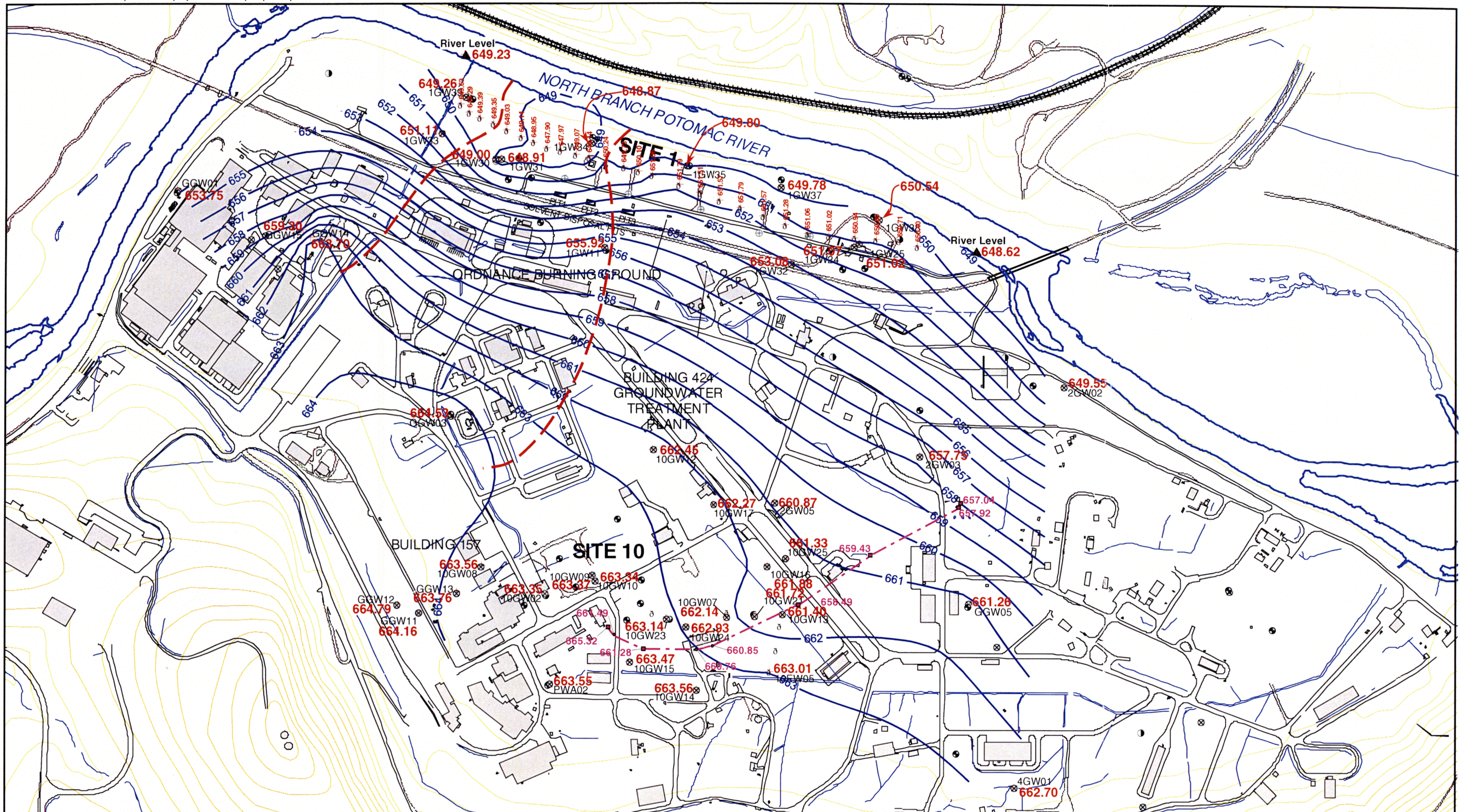

Legend

- ȣ Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ● Monitoring Well - Bedrock
- 663.86 Measured Water Level
- 621.28 Sewer Invert Elevation
- Equipotential
- Storm Sewer
- Estimated Capture Zone Boundary

N

400 0 400 800 Feet

Figure 4-14
Potentiometric Surface and Water Levels in the Alluvial Aquifer on July 10, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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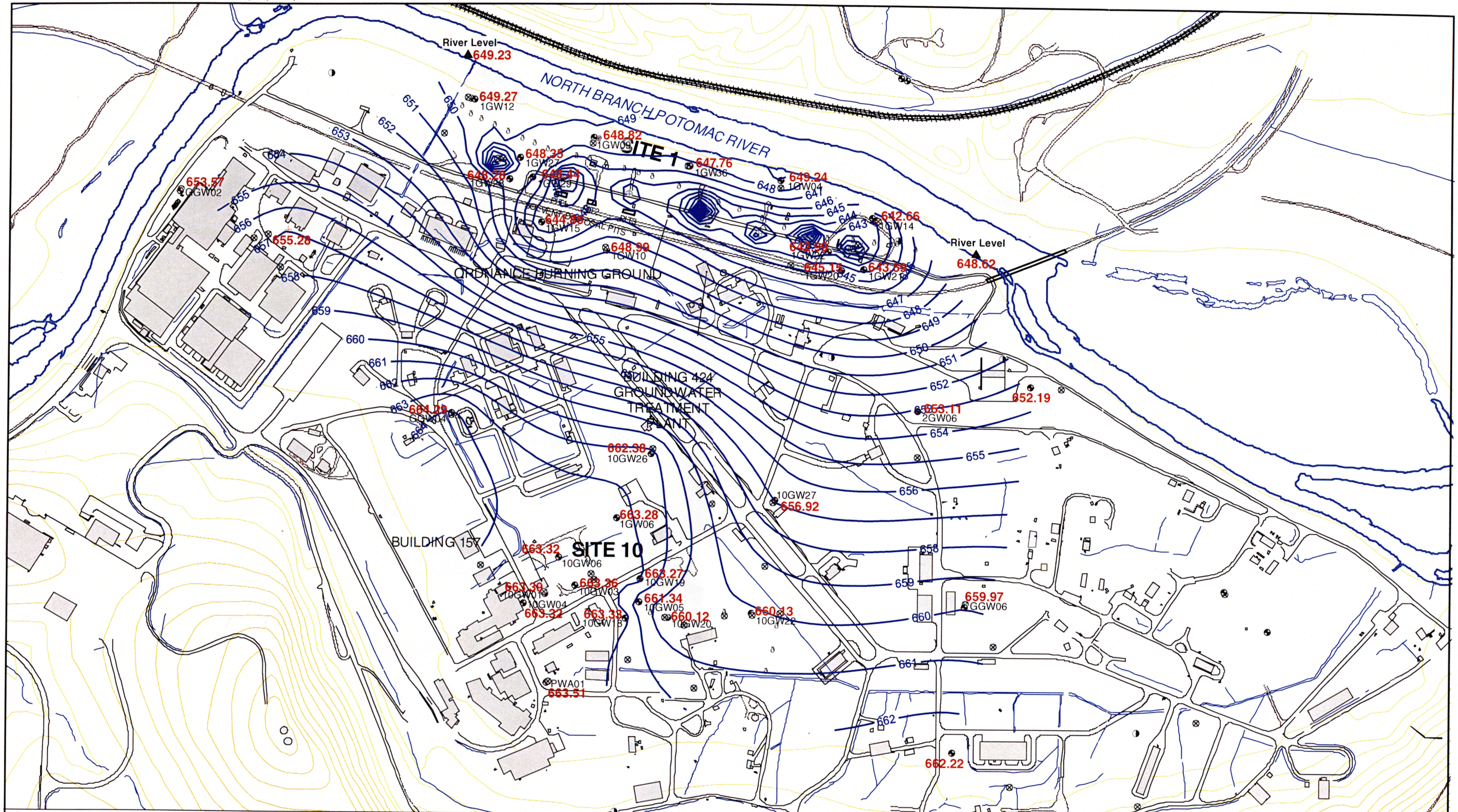

Legend

- ϑ Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ● Monitoring Well - Bedrock
- **663.86** Measured Water Level
- — Equipotential

400 0 400 800 Feet

N

Figure 4-15
Potentiometric Surface and Water Levels in the Bedrock Aquifer on July 10, 2001
Phase III Aquifer Testing at site 1 and Site 10
Allegany Ballistics Laboratory

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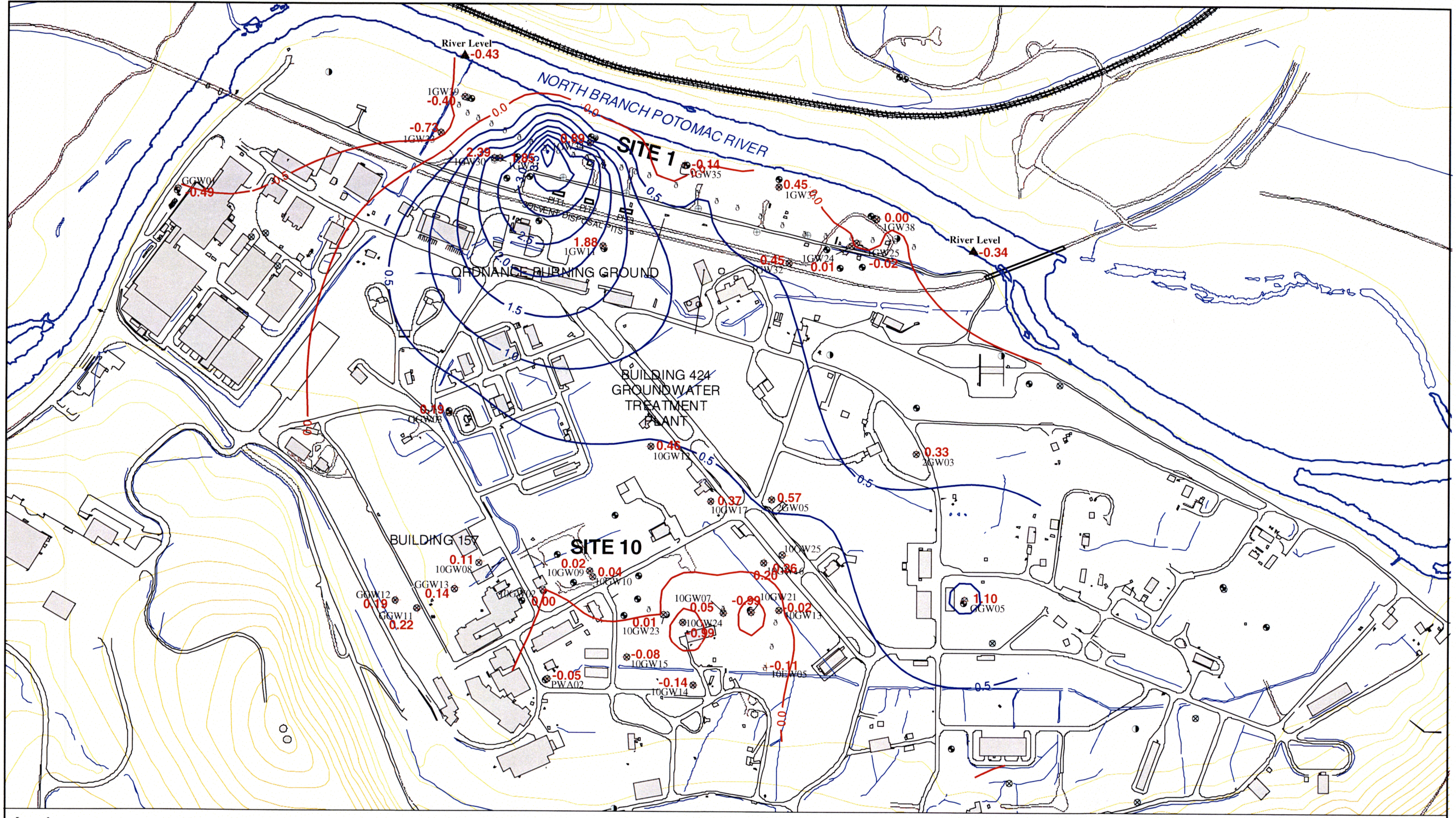

Legend

- ꝺ Extraction Well - Alluvial
- ⊕ Extraction Well - Bedrock
- ◑ Monitoring Well - Hybrid
- ⊗ Monitoring Well - Alluvial
- ● Monitoring Well - Bedrock
- 0.57 Measured Drawdown (negative where water level increased)
- Positive Drawdown Contour
- Zero or Negative Drawdown Contour

N

400 0 400 800 Feet

Figure 4-16
Drawdown Measured in the Alluvial Aquifer During the Bedrock Aquifer Test, July 2 to July 10, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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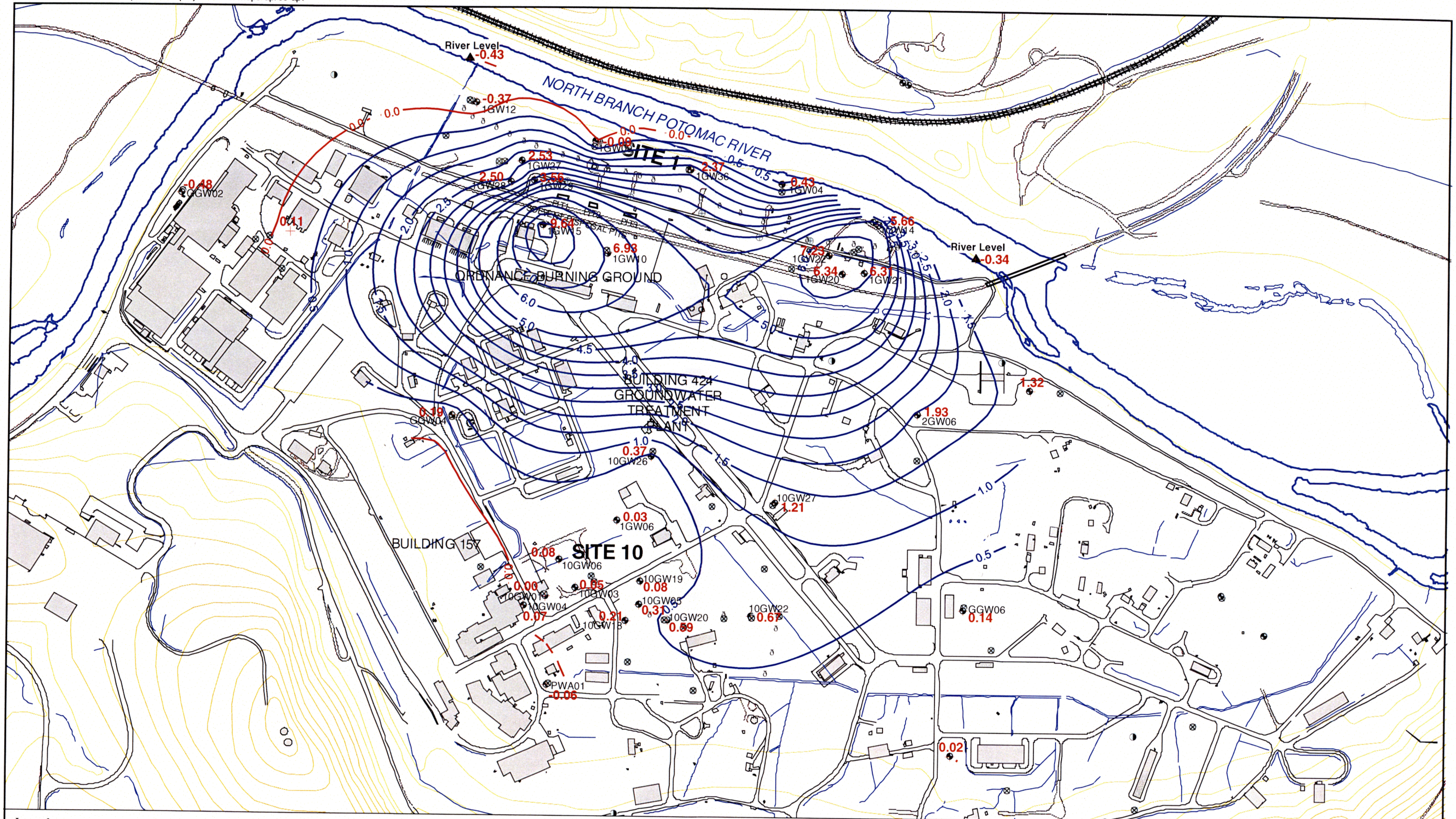

Legend

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Hybrid
- Monitoring Well - Alluvial
- Monitoring Well - Bedrock
- 0.57 Measured Drawdown (negative where water level increased)
- Positive Drawdown Contour
- Zero or Negative Drawdown Contour

N

400 0 400 800 Feet

Figure 4-17
Drawdown Measured in the Bedrock Aquifer During the Bedrock Aquifer Test, July 2 to July 10, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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5.0 Groundwater Modeling

5.1 Model Scope and Purpose

A numerical groundwater flow model was developed to cover the western and central parts of Plant 1 including all of sites 1 and 10. Previous groundwater modeling at sites 1 and 10 was done with small local models that were used to evaluate planned groundwater extraction systems. These previous models, documented in the Phase I Aquifer Testing Report (CH2M HILL, December 1998), dealt separately with groundwater flow in the east and west parts of Site 1 and in the alluvial aquifer alone at Site 10. They could not represent the hydraulic interactions that have been observed between the sites. The new groundwater flow model ties these areas together so that the groundwater flow system, including both alluvium and bedrock at sites 1 and 10, can be treated as a unified whole.

The new unified groundwater flow model for sites 1 and 10 was developed for the following specific purposes:

- To provide a framework for interpreting the results of the large-scale bedrock test through model calibration.
- To support the design of enhancements to the Site 10 groundwater extraction system that will address both bedrock and alluvial contamination at Site 10 under the influence of the hydraulic effects of the extraction system at Site 1.

5.2 Hydrogeologic Conceptual Model

5.2.1 Flow Domain

Groundwater flow at Plant 1 occurs in the bedrock and in the saturated portion of the overlying alluvium. The saturated thickness of the alluvium ranges from approximately 5 feet to 30 feet, but is between 15 and 25 feet in most areas. Groundwater flow in the bedrock takes place in the fractures and bedding planes. The maximum depth to which flow persists is unknown. The great majority of wells drilled into the bedrock are less than 100 feet deep, which means that they penetrate less than 70 feet into bedrock. It is assumed that fracture apertures and bedding plane partings are reduced with depth because of the increasing pressure of overburden, and that the majority of groundwater flow occurs in the upper 100 feet of bedrock.

The North Branch Potomac River is believed to be a discharge boundary to groundwater flow in both the alluvium and the bedrock on the north and west sides of Plant 1. To the south of Plant 1, the alluvium is bounded by the base of Knobly Mountain. There is probably some groundwater inflow to Plant 1 through the bedrock in this area. However, the greater part of the groundwater flow in both alluvium and bedrock is believed to arise from direct infiltration of precipitation at the ground surface within the Plant 1 area.

5.2.2 Aquifer Properties

Aquifer tests have been performed at both Site 1 and Site 10 as part of pre-design testing for the groundwater extraction systems at those sites. The results of those aquifer tests were reported in the Phase I Aquifer Testing Report (CH2M HILL, December 1998). The Phase II Aquifer Testing at Site 1 Report (CH2M HILL, September 1999a), and the Phase II Aquifer Testing at Site 10 Report (CH2M HILL, September 1999b). The test methods included step-drawdown tests, yield tests, and constant-rate pumping tests with multiple observation wells. The step-drawdown and yield tests served mainly to determine the productivity of the wells, but also gave an indication of the spatial variations in aquifer parameters. The constant-rate pumping tests yielded data that helped to quantitatively characterize the aquifers.

Constant-rate aquifer tests have consistently shown that the alluvial and bedrock aquifers behave as distinct hydrologic units, but with a limited degree of hydraulic interaction characteristic of leaky aquifers. Hydraulic separation between the aquifers, as revealed in the pumping tests, is somewhat surprising because there is no apparent low-permeability unit physically separating them. Most boring logs show that the alluvial materials become coarser with depth and lie directly on the surface of the bedrock. In the absence of an obvious semi-confining unit, hydraulic separation between the aquifers is attributed to anisotropy in the bedrock, with the vertical component of hydraulic conductivity being substantially lower than the horizontal components.

5.2.2.1 Alluvial Aquifer Properties

The alluvial aquifer is composed of floodplain deposits that are generally 20 to 30 feet thick. They consist of clay, silt, sand, and gravel. From the ground surface to depths of 10 to 15 feet, the alluvial material is predominantly silt and clay. Below this is an alluvial layer of poorly sorted sand, gravel, and pebbles that generally becomes coarser with depth. In many places, a layer of cobbles with varying amounts of silt and clay is found at the base of the alluvium. The bottom 10 to 20 feet of the alluvium is saturated, forming the alluvial aquifer.

Although there is considerable spatial variability in aquifer materials and properties, the granular nature of the aquifer provides no basis for horizontal anisotropy. Table 5-1 summarizes the results of nine constant-rate aquifer tests performed at sites 1 and 10 in past investigations. Three tests were run in wells completed in the alluvium and six were run in the bedrock. In general, the results show a high degree of spatial variability in both hydrogeologic units.

Test results for the alluvium show that the hydraulic conductivity is higher at the east end of Site 1 (test well 1GW25) than at the west end (test well 1GW31). The results for those two tests show only one value for each parameter because only one observation well was used in each case. For the alluvial aquifer test at Site 10 (test well 10GW11), two observation wells were used, resulting in a range of estimated flow properties. This suggests that the alluvial aquifer properties are spatially variable not only between sites, but also within a given site. The test results suggest that the hydraulic conductivity in the alluvium at the west end of Site 1 is lower than at the east end, and also lower than at Site 10.

5.2.2.2 Bedrock Aquifer Properties

The bedrock at Plant 1 is composed mainly of shale and limestone. Plant 1 bedrock is divided into eastern and western portions by the Wills Mountain Anticline, which is believed to trend north-northeast through Plant 1, passing through both sites 1 and 10. Bedrock encountered on the east side of the anticline is nearly all shale, but with some calcite veins. These shale beds dip gently toward the east at an angle of 30 degrees or less. On the west side of the anticline, the shale is interbedded with limestone, and the bedding planes are nearly vertical.

Groundwater flow in the bedrock is controlled by fractures and bedding plane partings. The hydraulic behavior of the extraction wells and monitoring wells completed in the bedrock suggests that the fractures are numerous, well distributed, and interconnected. When considered at the site scale, groundwater flow in the bedrock appears to be fairly well represented by the analytical methods developed for porous media. However, the controlling influences of fracture sets and bedding planes give rise to preferred flow directions that require consideration of horizontal and vertical anisotropy in the assignment of aquifer properties. At the scale of individual wells and well pairs, groundwater flow in the bedrock may be dominated by the specific fractures encountered, and is therefore much less predictable.

Table 5-1 lists the results of six bedrock aquifer tests that have been run at sites 1 and 10 in previous investigations. Each of those aquifer tests used multiple observation wells and generated ranges of estimated aquifer properties. The five wells tested at Site 1 are arrayed along an east-west line approximately 200 to 400 feet from the North Branch Potomac River. They are all currently being used as bedrock extraction wells at Site 1. The aquifer tests at wells 1GW23 and 1GW26, at both ends of the line, were conducted using a diamond-shaped array of observation wells for the purpose of detecting horizontal anisotropy. Analysis of the results indicated anisotropy ratios of approximately 15:1 at the west end of Site 1 and from 5:1 to 9:1 on the east end. At both ends of Site 1 the preferred horizontal flow direction in the bedrock was observed to be parallel to the river.

The single bedrock aquifer test at Site 10 used two observation wells and produced two transmissivity estimates that differed by only about 25 percent. Both transmissivity estimates were substantially higher than the transmissivity ranges obtained from the Site 1 tests. The observation wells used in the Site 10 test were not ideally oriented for evaluation of horizontal anisotropy, and no such evaluation was made.

The test results for the bedrock wells generally showed behavior characteristic of leaky aquifers, and permitted quantitative estimates of the leakance value to be made. However, the leakance estimates were generally quite variable, ranging over one to three orders of magnitude for the different observation wells in a single test. The leaky behavior observed in the bedrock aquifer tests is attributed to a limited hydraulic interconnection between the bedrock and alluvial aquifers.

5.3 Code Selection

Development of the unified groundwater flow model was based on the United States Geological Survey's (USGS) modular three-dimensional finite-difference code popularly known as MODFLOW. The specific version used was MODFLOW-2000 (Harbaugh, *et al.*, 2000). This version is the third major revision of the MODFLOW code, which was first released for public use in 1984 (McDonald and Harbaugh, 1984). It incorporates several simulation modules that were developed as add-ons to the basic code, and permits more flexibility in the formatting of input data. It also includes built-in capability for automated parameter estimation, which was helpful during model calibration. A specific feature of MODFLOW–2000 that was essential for the unified model at ABL Plant 1 was the ability to spatially vary horizontal anisotropy values within a given model layer. The original version of the code required horizontal anisotropy to be uniform for each model layer. Even with the ability to vary anisotropy within a layer, the MODFLOW-2000 code requires that the principle directions of anisotropy be aligned with the finite-difference grid.

5.4 Model Grid and Boundary Conditions

5.4.1 Grid Configuration

The horizontal configuration of the model grid is shown in Figure 5-1. It consists of 80 rows and 113 columns of finite-difference cells. The cell dimensions vary from a minimum of 30 feet to a maximum of 38 feet, with the finer grid spacing being assigned to the areas of groundwater extraction at sites 1 and 10. The grid orientation is rotated 20 degrees clockwise from north so that the rows are approximately parallel to the North Branch Potomac River as it bounds Site 1 on the north. This aligns the grid approximately with the estimated principle directions of bedrock anisotropy.

The model grid is discretized vertically into two layers, one for the alluvium and one for the bedrock. The top layer (Layer 1) is modeled as unconfined so that its vertical extent is limited below by an assigned array of bottom elevations and above by the computed elevation of the water table. The bottom elevation of Layer 1 was assigned to coincide with the structural surface of the top of bedrock, which is illustrated in Figure 5-2. Model Layer 2 represents the bedrock aquifer. It was assigned a uniform thickness of 100 feet, with its top corresponding to the bottom of Layer 1.

The horizontal grid configuration shown in Figure 5-1 includes only the active portion of the grid. Three types of boundary conditions were assigned along the edges of the active grid: river boundaries, general-head boundaries, and no-flow boundaries. The boundary condition types and the affected boundary cells are shown in the figure.

5.4.2 External Boundaries

5.4.2.1 River Boundaries

Grid cells at the North Branch Potomac River in both model layers were specified as head-dependent-flux boundary conditions using the MODFLOW river cell option. A MODFLOW river cell permits flow into or out of the model to occur at a rate determined by the calculated piezometric head at the cell in relation to reference elevations specified by the model user. Input values must be provided for each river cell specifying the water level in the river and the river bed elevation. If the calculated piezometric head in the cell is above the specified river bed elevation, the flow into the cell from the river is calculated as follows:

$$Q_{riv} = C_{riv}(H_{riv} - h)$$

where

- Q_{riv} is the flow into or out of the cell,
- C_{riv} is a user-specified river bed conductance term,
- H_{riv} is the user-specified water surface elevation in the river,
- h is the piezometric head in the aquifer cell or the river bed elevation, whichever is higher.

If the simulated piezometric head in the aquifer cell is lower than the user-specified river bed elevation, then the bed elevation is used in place of h in the equation for Q_{riv}. The water surface elevation values specified for the river boundary cells were interpolated from measured water levels between the upstream and downstream staff gauges at Site 1. Outside the river reach between the staff gauges, the river levels were estimated. The bed conductance values for the river boundary cells were adjusted during model calibration to improve the agreement between simulated and measured groundwater levels near the river.

5.4.2.2 General-Head Boundaries

Grid cells along the southern edge of the active grid, at the base of Knobly Mountain, were assigned head-dependent-flux boundary conditions in both layers using the MODFLOW general-head boundary (GHB) option. The GHB cell regulates flow into and out of the grid using an algebraic rule that is similar to the river cell, namely:

$$Q_{GHB} = C_{GHB}(H_{GHB} - h)$$

where

- Q_{GHB} is the flow into or out of the cell,
- C_{GHB} is a user-specified boundary cell conductance term,
- H_{GHB} is the user-specified reference elevation for the boundary cell,
- h is the piezometric head in the aquifer cell.

This type of boundary is essentially the same as the river boundary except that there is no river bed elevation that changes the application of the governing equation.

The boundary elevations (H_{GHB}) assigned to these boundary cells were extrapolated from the contoured potentiometric surfaces based on water-level the measurements of July 2, 2001. The GHB cell conductance values were assigned a moderate value of 100 ft^2/day, which permits groundwater from beyond the model to enter each GHB cell at a rate of approximately 0.52 gallons per minute per foot of drawdown below the reference elevation.

5.4.2.3 No-Flow Boundaries

No-flow boundary conditions were used in both layers along the eastern edge of the model. This boundary condition permits the potentiometric heads at the boundary cells to be calculated by the model under the constraint that the hydraulic gradient perpendicular to the boundary must be zero. In practical terms, it requires that the simulated flow directions at the boundary are parallel to the boundary. This condition approximates the observed groundwater flow patterns at the eastern edge of the model area, where flow is generally toward the North Branch Potomac River.

5.4.3 Hydrologic Stresses

Hydrologic stresses applied to the model represent the effects of groundwater sources and sinks applied in the interior parts of the model grid. These include specified inflow due to distributed recharge at the ground surface, specified pumping rates of the extraction wells at sites 1 and 10, and a head-dependent linear sink representing a leaking storm drain at Site 10, which was simulated using the MODFLOW drain cell option.

5.4.3.1 Recharge

A uniform recharge rate was applied in the top model layer to represent the average rate of infiltration to the water table due to precipitation. An initial recharge rate of 24 inches per year was tried at the start of model calibration, but was found to be too high. Through calibrations adjustments, a recharge rate of 12 inches per year was found to provide the best model results. This is approximately one fourth of the average annual precipitation.

5.4.3.2 Wells

The only active pumping wells within the model area are the extraction wells associated with the groundwater remediation efforts at sites 1 and 10. These wells are represented as point sinks at the centers of the affected model cells. Because the model grid uses a grid spacing of 30 feet in the groundwater extraction areas, the locations of these wells are represented accurately to within about 15 feet or less. The simulated pumping rates of the wells were based on measured rates from the flow meters and varied from one modeling scenario to another.

5.4.3.3 Drain Cells

An old storm drain line in the eastern part of Site 10 has been identified as a partial groundwater sink in the alluvial aquifer. This drain line was the subject of a special field investigation (CH2M HILL, October 2001) which found that it is buried slightly below the normal water table elevation and that groundwater enters it at varying rates depending on the height of the water table. This linear feature was simulated by a line of head-dependent-flux cells using the MODFLOW drain cell option in Layer 1 of the model, as shown in Figure 5-1.

The MODFLOW drain cell is very similar to the GHB cell except that it only permits outflow from the aquifer. The modeler must specify the drain elevation and the drain conductance. If the simulated piezometric head in the cell is higher than the drain elevation, MODFLOW calculates an outflow rate using an equation analogous to the GHB cell equation. However, if the piezometric head is below the drain elevation, the drain flow is zero.

The drain cell elevations specified in the model were interpolated from the pipe invert elevations measured in the storm drain manholes. The drain cell conductance values were calculated by multiplying the length of storm drain in each cell by 1.8 ft/day. This value of conductance per unit length of drain was calculated from the field measurements of groundwater inflow to the drain and the local water table elevations at the time the flow was measured.

5.5 Aquifer Properties

The aquifer properties required as input to the model for steady-state simulations are the three principal components of hydraulic conductivity: K_x (horizontal along the model rows), K_y (horizontal along the model columns), and K_z (vertical). For transient simulations, it is also necessary to supply model input defining the storage properties of the aquifers. For the confined flow conditions of Layer 2, storage is defined by the storage coefficient. For unsaturated flow conditions, as in Layer 1, the storage parameter is the specific yield.

5.5.1 Hydraulic Conductivity in Layer 1

Because the alluvial aquifer is a granular porous medium, the hydraulic conductivity in Layer 1 of the model was assumed to be isotropic. That is, all three principal components of the hydraulic conductivity were assigned the same value. However, it was clear from aquifer testing results and experience in monthly mapping of the potentiometric surface that the isotropic hydraulic conductivity of Layer 1 is not uniformly distributed across the model area. Therefore, the approach taken in assigning the hydraulic conductivity distribution was to divide the model layer into distinct zones with a uniform isotropic hydraulic conductivity value for each zone.

In the initial model setup, the delineation of hydraulic conductivity zones was based on inspection of the alluvial potentiometric surface maps to identify areas where distinct differences in the horizontal hydraulic gradients were apparent. To eliminate the complicating effects of drawdown around the extraction wells, the inspection focused on the potentiometric surface map for July 2, 2001, which was near the end of the recovery period of the bedrock test. The initial zone delineation also took account of the differences in aquifer testing results for the alluvial aquifer, as listed in Table 5-1. The hydraulic conductivity estimates obtained from the aquifer tests were used as the initial values assigned to the zones in the model setup. However, as model calibration progressed it was necessary to revise the initial zone delineation and even to add new zones to improve the match between field observations and the simulation results. Figure 5-3 shows the calibrated distribution of hydraulic conductivity developed for Layer 1.

The lowest value of hydraulic conductivity, 12.57 ft/day, was assigned to the zone identified by black cross-hatching in Figure 5-3. That zone includes much of the west end of Site 1 and forms a band across the area separating Site 1 and Site 10. The hydraulic conductivity for that zone is close to the value determined by aquifer testing at well 1GW31 (9 ft/day), but had to be increased slightly from the test value to improve model calibration.

Near the east end of Site 1, a higher hydraulic conductivity of 27.4 ft/day was assigned to the zone shown with red cross-hatching in Figure 5-3. That zone includes well 1GW25, which was tested in Phase I, resulting in a hydraulic conductivity estimate of 86 ft/day. The aquifer test result from well 1GW25 was found to be too high to produce realistic simulation of hydraulic gradients in that area, and the lower value of 27.4 ft/day was selected through model calibration. This same value of hydraulic conductivity was assigned in two other areas of model layer 1, as shown in the figure.

Substantial differences between the hydraulic conductivity values estimated from aquifer tests and those found necessary for reasonable model calibration are probably due to the differences of scale between the model and the aquifer test. The distances from the test well to the observation wells in the Phase I alluvial aquifer tests were less than 30 feet. Model calibration, on the other hand, was based on gradients measured between wells that are hundreds of feet apart. In an aquifer with highly non-uniform properties, it is to be expected that analyses based on such widely differing scales of measurement would produce somewhat different results. For the purposes of this groundwater flow model, the properties derived from large-scale observations are more useful than those derived from single wells or closely spaced well pairs.

The highest hydraulic conductivity value used in simulating the alluvial aquifer was 63.33 ft/day. This value was used in two areas, as shown by the blue cross-hatching in Figure 5-3. One of the areas with high hydraulic conductivity was the western portion of Site 10. An aquifer test conducted there at well 10GW11 (now called 10EW36) produced hydraulic conductivity estimates of 41 ft/day and 109 ft/day for two different observation wells. The calibrated hydraulic conductivity in the model is the same as the geometric mean of the two aquifer test estimates. A second zone of high hydraulic conductivity was used along the south bank of the North Branch Potomac River and under the river bed, where relatively low hydraulic gradients were measured.

5.5.2 Hydraulic Conductivity in Layer 2

Model Layer 2 represents the bedrock aquifer, where the flow properties depend on the locations, orientations, and interconnections of fractures and bedding planes in the rock. Initial assignment of hydraulic conductivity values in Layer 2 was guided by a combination of geologic mapping, aquifer testing results, and the observed patterns of hydraulic gradients in the bedrock.

Figure 5-4 presents a geologic map of Plant 1 and the surrounding area, showing the distribution of rock types, and the strike and dip of the rock strata. A feature of particular importance is the Wills Mountain Anticline, which passes from north to south through both sites 1 and 10. On the east side of the anticline the bedrock is nearly all shale, and the bedding dips gently toward the east at an angle of 30 degrees or less. On the west side of the anticline the bedding planes are nearly vertical. Consequently, the anticline is a logical place for a zonal boundary that divides the bedrock aquifer into sections with differing aquifer properties. Because of the nearly vertical bedding west of the anticline, significant horizontal anisotropy is to be expected, with preferred groundwater flow parallel to the anticline. However, in the Phase I aquifer testing program, aquifer tests were performed at Site 1 both east and west of the anticline. These tests showed that the bedrock near the North Branch Potomac River has preferred flow parallel to the river (perpendicular to the anticline). This is believed to be caused by fracturing or faulting that may have occurred after the anticline was formed and which is probably responsible for the present orientation of the river on the north side of Site 1. The need for differing anisotropy properties near the river led to further subdivision of the simulated bedrock properties. Other hydraulic conductivity zone boundaries were delineated as the result of observed differences in the horizontal hydraulic gradients in the bedrock.

Figure 5-5 shows the model's calibrated hydraulic conductivity distribution in Layer 2, which represents the bedrock aquifer. Each aquifer zone was assigned three components of hydraulic conductivity. The K_x component is the hydraulic conductivity component parallel to the grid rows, which are aligned with the North Branch Potomac River at Site 1. The K_y component is parallel to the grid columns, or perpendicular to the river at Site 1. The K_z component is vertical and controls simulated groundwater flow between the alluvium and the bedrock.

On the east end of Site 1, the area of Figure 5-5 shown with dark blue cross-hatching, the x-component of hydraulic conductivity (4.0 ft/day) is 12.5 times greater than the y-component (0.32 ft/day). A Phase I aquifer test was conducted in this area at well 1GW23 (now called 1EW34). Four observation wells were used in the test, and the transmissivity estimates ranged from 224 ft^2/day to 369 ft^2/day. Because the bedrock aquifer is simulated with a thickness of 100 feet, the equivalent hydraulic conductivity values would range from 2.24 to 3.69 ft/day. These estimates were calculated using conventional formulas of well hydraulics, which assume radial flow to the test well in a uniform isotropic aquifer. A subsequent analysis of bedrock anisotropy at well 1GW23 gave estimates of K_x/K_y ranging from 5 to 9. Thus, the calibrated hydraulic conductivity at the east end of Site 1 has a slightly higher anisotropy ratio than was indicated by the aquifer test. The higher anisotropy ratio was found to give better simulation of the drawdown pattern observed during the pumping segment of the large-scale bedrock test.

The west side of Site 1 was assigned isotropic hydraulic conductivity components of K_x = 1.4 ft/day and K_y = 7 ft/day. This results in an anisotropy ratio of 0.2 with preferred flow toward the river and parallel to the trend of the anticline and to the strike of the nearly vertical bedding. The aquifer test run in this area at well 1GW26 (now 1EW28) during Phase I testing yielded hydraulic conductivity values ranging from 0.41 to 1.06 ft/day. Thus, the calibrated hydraulic conductivity components are higher than the estimates from the aquifer test by 3 to 7 times. Furthermore, the aquifer test data suggested preferred flow parallel to the river (i.e. the same orientation as at the east end of the site). However, use of hydraulic conductivity components similar to those estimated from the test at well 1EW28 in the groundwater flow model produced unrealistic simulations of the potentiometric surface in that area. Observations of the bedrock potentiometric surface and of the drawdown during the bedrock test suggest that the bedrock characteristics are highly non-uniform around well 1EW28. This nonuniformity may have caused the results of the aquifer test to be misleading.

The calibrated hydraulic conductivity on the west side of Site 10 (the green area in Figure 5-5) is based on the results of the Phase I aquifer test at well 10GW01. An anisotropy ratio of 0.2 was used, with preferred flow toward the river. The geometric mean of the two horizontal hydraulic conductivity components is 14.36 ft/day, which is in the middle of the range of estimates obtained from the aquifer test.

In the area between Site 1 and Site 10, the calibrated hydraulic conductivity is generally lower than at the sites themselves. On the west side of the anticline, where the bedding of the rock is nearly vertical (red and yellow zones in Figure 5-5), an anisotropy ratio of 0.2 was used to favor groundwater flow parallel to the anticline. The calibrated hydraulic conductivity east of the anticline (black and light blue zones in Figure 5-5) was horizontally isotropic. This is reasonable, given the nearly horizontal orientation of the bedding in this area. The final simulated values of the hydraulic conductivity components were determined as necessary to match the observed pattern of hydraulic gradients between the sites.

Figure 5-5 also shows two relatively long and narrow zones with high values of hydraulic conductivity in the eastern part of Layer 2. The larger of these zones is shown with light blue cross-hatching, and has isotropic horizontal hydraulic conductivity components of 12.82 ft/day. This zone connects the eastern part of Site 10 with the eastern part of Site 1. Its presence is suggested by the form of the bedrock potentiometric surface and by the propagation of drawdown from the Site 1 bedrock wells to the east side of Site 10 during the bedrock test. The relatively high hydraulic conductivity in this zone is mainly responsible for the predominantly eastward flow at Site 10 and the tendency for flow in the bedrock to converge toward the northeast corner of that site. The bedrock properties that are responsible for the enhanced hydraulic conductivity in that zone are not known, but likely are associated with fracturing concentrated in the area.

Another linear zone of high hydraulic conductivity was assigned to the bedrock at the east end of Site 1 in the calibrated model. The zone is oriented parallel to the river, has the width of one column of cells, and is shown with green cross-hatching. This feature has not been indicated by any subsurface exploration, but was found to be necessary for improvement of model calibration.

Evidence to support the presence of this linear zone of high hydraulic conductivity comes from examination of the natural bedrock potentiometric surface and the pattern of bedrock drawdown during the bedrock pumping test. The potentiometric surface under non-pumping conditions observed on July 2, 2001 shows strong hydraulic gradients across the diamond-shaped group of wells 1GW20, 1GW21, 1GW22, and 1EW34, indicating groundwater flow toward the river. North of those wells, however, the gradient between 1EW34 and 1GW14 is considerably smaller. From this evidence alone, it could be concluded that a zone of high hydraulic conductivity exists between well 1EW34 and the river, which depresses the water levels in well 1EW34 and causes high gradients to the south. However, during the pumping phase of the bedrock test, well 1GW14, which is within 100 feet of the river bank, experienced more than 5 feet of drawdown. That would not happen if the aquifer at well 1GW14 had a good hydraulic connection to the river. Therefore, it cannot be good communication with the river in that area that causes low water levels at well 1EW34 during non-pumping conditions. The connection must be elsewhere. During model calibration, it was found that the narrow zone of very high hydraulic conductivity, shown as a green bar in Figure 5-5, can produce a simulation that closely mimics both the non-pumping gradients and the eastward propagation of drawdown experienced during the bedrock test. This may be a zone of densely concentrated post-folding fractures.

The vertical component of hydraulic conductivity, K_z, was assigned a value of 0.033 ft/day throughout most of Layer 2. When divided by half the layer thickness (50 feet), this is equivalent to a leakance value of 0.00066/day. For comparison, the leakance estimates obtained from previous aquifer tests ranged from 0.0003 to 0.95/day (see Table 5-1). The vertical hydraulic conductivity values used in the model were determined by trial-and-error adjustment supplemented by the automated parameter estimation capability of the MODFLOW-2000 code. Exceptions to the generally-applied value of 0.033 ft/day occurred in two areas. One was the zone on the east side of Site 1 (with dark blue cross hatching), where a lower value of 0.005 ft/day was found to be necessary to improve calibration in that area. The second was in the small area on the west-central side of Site 1, which is shown with solid magenta coloring in Figure 5-5. A relatively high value of 1 ft/day was used for the vertical hydraulic conductivity component there because of the strong drawdown response observed at alluvial extraction well 1EW20 during the bedrock pumping test. This may be due to enhanced fracturing of the bedrock along the axis of the anticline.

5.6 Calibration Results

5.6.1 Calibration to Non-Pumping Conditions

The model calibration was judged against two data sets collected during the bedrock test. One was the pair of natural potentiometric surfaces measured in the alluvium and the bedrock on July 2, 2001, at the end of the recovery period. The second was the drawdown distribution observed in both aquifers during the bedrock pumping segment of the test.

Figure 5-6 shows a direct overlay of the simulated alluvial potentiometric surface on the measured potentiometric surface and water levels for the non-pumping conditions of July 2, 2001. The figure shows reasonable agreement in the magnitude and distribution of the horizontal gradients and the directions of the equipotentials. The best match between simulated and measured heads occurs at Site 1 and in the area between Site 1 and Site 10. This is also the area of greatest importance with respect to the model objectives.

Both the measured and simulated water levels indicate very low hydraulic gradients on the west side of Site 10. Although the simulated water levels in that area are within 1 foot of the measured water levels, the directions of the equipotentials are somewhat different. The measured water levels indicate a more pronounced easterly flow trend than could be obtained with the model.

Table 5-2 lists the measured water levels, simulated water levels, and the model residuals (difference between measurements and simulations) at 64 monitoring wells in the alluvium. The greatest residual was 1.23 feet at well 1EW26, and the minimum was –1.36 feet at well 1EW20. The mean residual in the alluvial aquifer was –0.074 feet. This indicates that the model has a slight negative bias in Layer 1, but the bias is less than 0.1 ft. The root mean square residual is an indicator of the accuracy of the simulation. A value of 0.667 ft indicates that the simulation was generally within about two thirds of a foot of the water-level measurements.

It should be noted that the measured water levels included two monitoring wells at Site 11 (GGW14 and GGW15) that are only about 70 feet apart, and yet had water levels that differed by 4.29 feet on July 2, 2001. The reason for that relatively large difference in water levels is unknown, and only the lower of the two, at GGW15, was used as a calibration target.

Figure 5-7 shows a pictorial comparison of simulated and measured water levels in the bedrock. Again the general pattern of gradients and equipotential directions match reasonably well. The match in the bedrock is slightly better than in the alluvium. The calibration statistics for the bedrock aquifer are listed in Table 5-3. This also shows slightly better calibration in the bedrock than in the alluvium, as both the mean residual and the root mean square are smaller. Overall, the potentiometric surface maps and the calibration statistics indicate a close correspondence between simulated and measured water levels under non-pumping conditions.

Yet another measure of the accuracy of the model in simulating natural groundwater flow conditions concerns the leaky storm drain on the eastern side of Site 10. Flow in the storm drain was measured on July 2, 2001 by installing a v-notch weir in the downstream manhole at Site 10 (CH2M HILL, October 2001). The measured flow rate of approximately 8 gpm was attributed to the infiltration of alluvial groundwater into the storm sewer upstream of the manhole. Drain boundary cells were used in the model to represent the capacity of this sewer line to act as a groundwater sink in the alluvial aquifer at Site 10. The simulated flow to the drain cells at Site 10 was 9.09 gpm, which is a good approximation of the measured sewer inflow.

5.6.2 Calibration to Drawdown During Bedrock Pumping

Because one of the modeling objectives was to characterize the hydraulic interactions between Site 1 and Site 10, it was important that the model be calibrated using drawdown observations from the bedrock pumping test as well as the non-pumping water levels. As described in a previous section, the drawdown observations were based on comparison of the water levels measured on July 10, at the end of the bedrock pumping period, with the non-pumping water levels measured on July 2, 2001. During that seven-day period, there were some weather-related changes in groundwater levels in addition to the drawdowns produced by turning on the bedrock extraction wells at Site 1. Therefore, the drawdown calibration targets in both the alluvium and the bedrock are less precisely known than the non-pumping water levels.

Figure 5-8 shows a direct overlay of the simulated drawdowns in Layer 1 with the alluvial drawdowns based on measured water levels. The maximum measured drawdown in the alluvium was detected at alluvial extraction well 1EW20, which was used as a monitoring well on both July 2 and July 10, when the alluvial wells were not being pumped. The maximum simulated drawdown also occurred near well 1EW20. The maximum simulated drawdown of about 3.8 feet was about a foot less than the measured drawdown of 4.88 feet at well 1EW20. The general pattern of simulated alluvial drawdown is qualitatively similar to the measured pattern. On the eastern side of Site 1, the simulated drawdown is slightly greater than was observed, but generally agrees within 1 foot or less. Closer to Site 10, there is good agreement in the locations of simulated and measured 0.5-foot drawdown contours.

Figure 5-9 shows the comparison between simulated and measured drawdown in the bedrock aquifer. Again, there is good agreement in the locations of the measured and simulated 0.5-foot drawdown contours near Site 10. This is very important because it clearly indicates the ability of the model to represent hydraulic interaction between the sites. Direct comparison of the maximum simulated and measured drawdowns is invalid for this aquifer because observed drawdown values were not calculated for the extraction wells themselves. Measurement of water levels in a pumping well are not considered to be valid estimates of the water level in the aquifer. The groundwater model, however, does calculate the theoretical drawdown in the cells containing the extraction wells, and they are included in the simulated drawdown contour map.

In the areas where monitoring wells were observed between Site 1 and Site 10, the measured and simulated drawdown distributions show generally similar characteristics. In some parts of the eastern third of the modeled area, where the monitoring wells are far apart, there are substantial differences between the measured and simulated drawdown contour distributions. One reason for this is that the observed drawdowns were contoured with a kriging algorithm that produces a relatively smooth and regularly-spaced set of contours between data points. The model, on the other hand, accounts for differences in groundwater flow in areas of the bedrock that were assigned different aquifer properties. Hence, part of the difference in these areas may relate to an oversimplified interpretation of the observed drawdown data.

In general, the calibration data suggest that the groundwater flow model provides a fairly accurate representation of both non-pumping water level distributions and the propagation of drawdown away from Site 1 when the bedrock wells are being pumped.

Table 5-1
Summary of Aquifer Parameters Derived from Previous Aquifer Testing
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Alluvial Aquifer Tests

Test Well	Range of Transmissivity Values (ft^2/day)	Range of Hydraulic Conductivity Values (ft/day)	Range of Storage Coefficients	Range of Specific Yields
1GW25	950	86	0.0009	0.105
1GW31	129	9	0.003	0.062
10GW11[1]	734 - 1964	41 - 109	0.007 – 0.015	0.072 – 1.0

Bedrock Aquifer Tests

Test Well	Range of Transmissivity Values (ft^2/day)	Range of Hydraulic Conductivity Values[2] (ft/day)	Range of Storage Coefficients	Range of Leakance Values (day^{-1})
1EW29	149 - 201	1.49 – 2.01	0.0001 – 0.04	0.0005 – 0.06
1EW31	189 - 536	1.89 – 5.36	0.0001 – 0.07	0.0008 – 0.95
1EW33	250 - 541	2.5 – 5.41	0.0002 – 0.1	0.0003 – 0.3
1GW23[3]	224 - 369	2.24 – 3.69	0.0001 – 0.002	0.0009 – 0.003
1GW26[4]	41 - 106	0.41 – 1.06	0.0008 – 0.001	0.0005 – 0.002
10GW01	1280 - 1608	12.8 – 16.08	0.0003 – 0.002	0.004 – 0.04

[1] Well 10GW11 was converted to an extraction well and renamed 10EW36.
[2] Assuming a thickness of 100 feet for the bedrock aquifer.
[3] Well 1GW23 was converted to an extraction well and renamed 1EW34.
[4] Well 1GW26 was converted to an extraction well and renamed 1EW28.

Table 5-2
Calibration Statistics for Model Layer 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Well	Measured Water Level* (Ft. above MSL)	Simulated Water Level (Ft. above MSL)	Simulation Residual (Ft.)
10EW05	662.90	662.764	-0.14
10GW02	663.35	664.235	0.89
10GW07	662.19	662.202	0.01
10GW08	663.67	664.459	0.79
10GW09	663.39	663.903	0.51
10GW10	663.38	663.892	0.51
10GW12	662.91	662.831	-0.08
10GW13	661.38	661.434	0.05
10GW14	663.42	663.349	-0.07
10GW15	663.39	663.595	0.21
10GW16	662.08	661.383	-0.70
10GW17	662.64	662.479	-0.16
10GW21	660.73	661.611	0.88
10GW23	663.15	663.105	-0.05
10GW25	661.59	661.014	-0.58
1EW01	650.34	649.595	-0.75
1EW02	650.79	649.811	-0.98
1EW03	650.83	650.139	-0.69
1EW04	650.95	650.407	-0.54
1EW05	651.07	650.681	-0.39
1EW06	651.16	650.912	-0.25
1EW07	651.41	650.948	-0.46
1EW08	651.82	650.935	-0.89
1EW09	651.82	651.047	-0.77
1EW10	652.04	651.079	-0.96
1EW11	651.99	650.948	-1.04
1EW12	651.79	651.045	-0.75
1EW13	651.11	651.120	0.01
1EW14	650.55	651.129	0.58
1EW15	651.07	651.332	0.26
1EW16	652.04	651.534	-0.51
1EW17	651.90	651.503	-0.40
1EW18	651.58	651.574	-0.01
1EW19	651.42	651.542	0.12
1EW20	652.78	651.417	-1.36
1EW21	651.09	650.967	-0.12
1EW22	650.18	650.693	0.51
1EW23	649.42	650.462	1.04
1EW24	649.59	650.300	0.71
1EW25	649.23	650.169	0.94
1EW26	648.81	650.038	1.23
1EW27	649.27	649.842	0.57
1GW11	657.80	656.983	-0.82
1GW24	651.08	650.606	-0.47

Table 5-2 (Continued)

Calibration Statistics for Model Layer 1

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

Well	Measured Water Level* (Ft. above MSL)	Simulated Water Level (Ft. above MSL)	Simulation Residual (Ft.)
1GW25	651.00	650.477	-0.52
1GW30	651.39	652.039	0.65
1GW31	650.76	651.817	1.06
1GW32	653.53	652.473	-1.06
1GW33	650.38	651.524	1.14
1GW34	649.76	649.953	0.19
1GW35	649.66	649.568	-0.09
1GW37	650.23	649.934	-0.30
1GW38	650.54	649.692	-0.85
1GW39	648.86	649.606	0.75
2GW05	661.44	660.769	-0.67
2-GW3	658.08	657.432	-0.65
GGW05	661.36	661.432	0.07
GGW-1	653.26	652.203	-1.06
GGW-11	664.38	664.779	0.40
GGW-12	664.98	664.816	-0.16
GGW-13	663.90	664.621	0.72
GGW15	659.04	658.716	-0.32
GGW-3	664.72	663.865	-0.86
PWA-2	663.50	664.423	0.92

Residual Arithmetic Mean = -0.074 ft

Root Mean Square Residual = 0.667 ft

*Water levels measured on July 2, 2001

Table 5-3

Calibration Statistics for Model Layer 2

Phase III Aquifer Testing at Site 1 and Site 10

Allegany Ballistics Laboratory

Well	Measured Water Level* (Ft. above MSL)	Simulated Water Level (Ft. above MSL)	Simulation Residual (Ft.)
10GW01	663.39	663.506	0.12
10GW03	663.41	663.411	0.00
10GW04	663.39	663.570	0.18
10GW05	661.65	662.899	1.25
10GW06	663.40	663.445	0.05
10GW18	663.54	663.296	-0.24
10GW19	663.35	663.053	-0.30
10GW20	660.71	660.373	-0.34
10GW22	660.80	660.042	-0.76
10GW26	662.75	662.659	-0.09
10GW27	658.13	657.887	-0.24
11GW11S	655.39	656.517	1.13
1EW28	650.75	650.442	-0.31
1EW29	654.37	653.453	-0.92
1EW30	653.85	653.907	0.06
1EW31	652.07	652.415	0.35
1EW32	652.74	651.816	-0.92
1EW33	649.65	650.260	0.61
1EW34	649.31	649.619	0.31
1GW10	655.92	656.519	0.60
1GW12	649.13	649.324	0.19
1GW14	648.32	648.991	0.67
1GW15	654.50	654.461	-0.04
1GW20	651.49	651.098	-0.39
1GW21	649.90	650.486	0.59
1GW22	650.22	650.507	0.29
1GW27	650.88	650.704	-0.18
1GW28	650.78	651.071	0.29
1GW29	652.00	652.039	0.04
1GW36	650.13	649.721	-0.41
1GW4	649.67	649.014	-0.66
1GW6	663.31	663.232	-0.08
1GW9	648.73	649.282	0.55
2GW07	653.51	652.174	-1.34
2-GW6	655.04	654.243	-0.80
GGW04	664.48	663.461	-1.02
GGW06	660.11	660.556	0.45
GGW-2	653.09	651.553	-1.54
PWA-1	663.45	663.567	0.12

Residual Arithmetic Mean = -0.070 ft

Root Mean Square Residual = 0.613 ft

*Water levels measured on July 2, 2001

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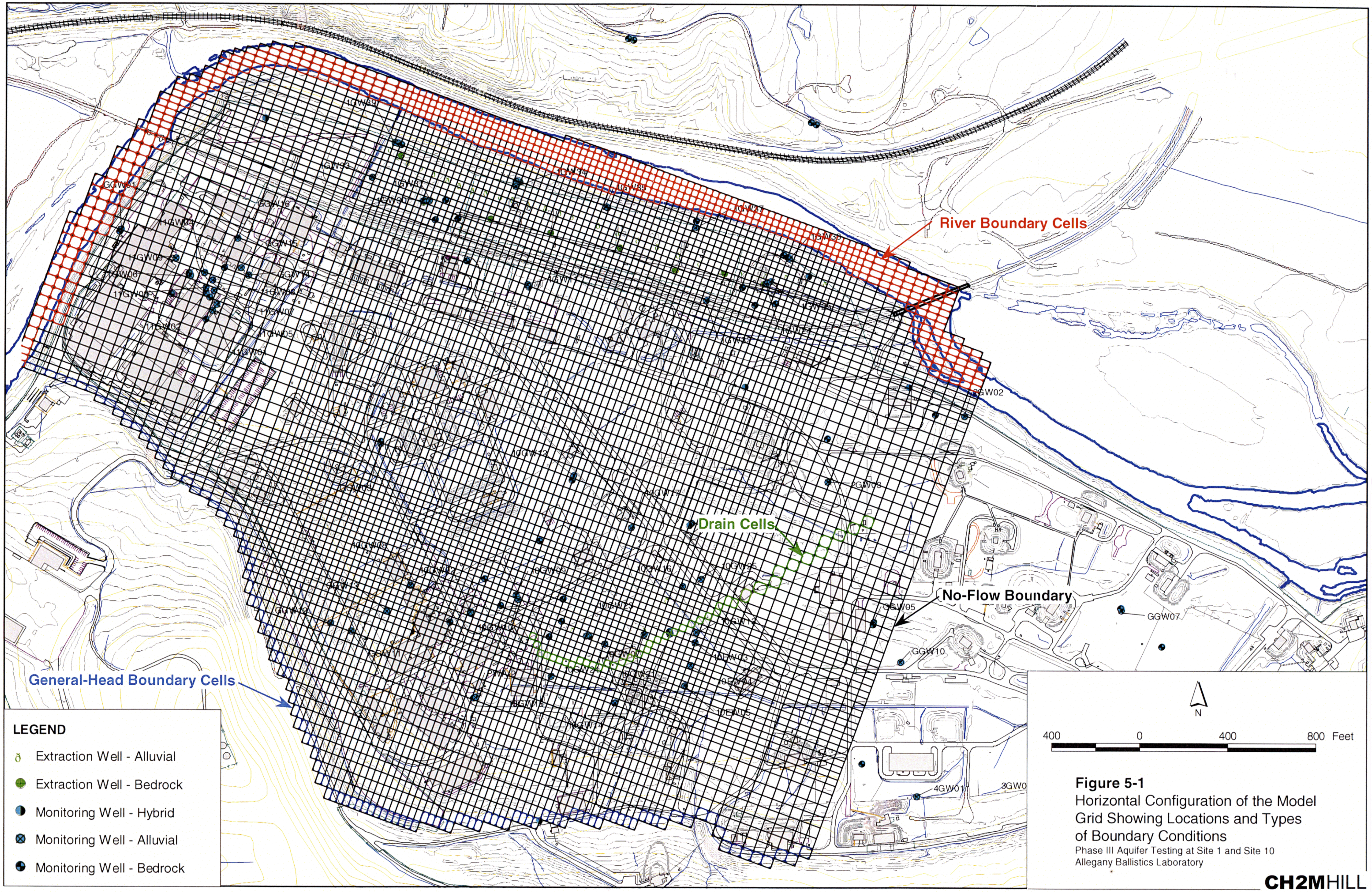

Figure 5-1
Horizontal Configuration of the Model Grid Showing Locations and Types of Boundary Conditions
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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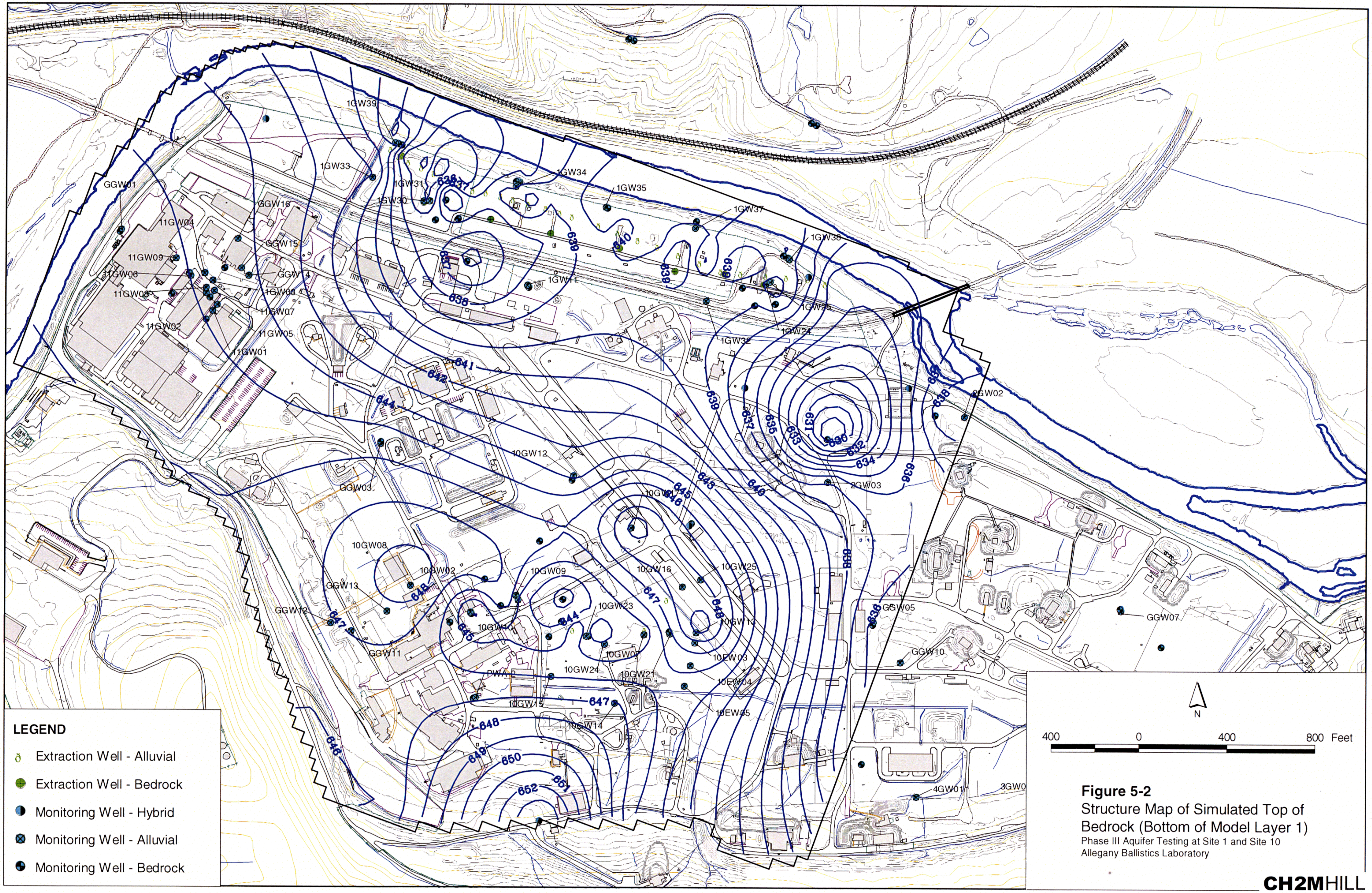

Figure 5-2
Structure Map of Simulated Top of Bedrock (Bottom of Model Layer 1)
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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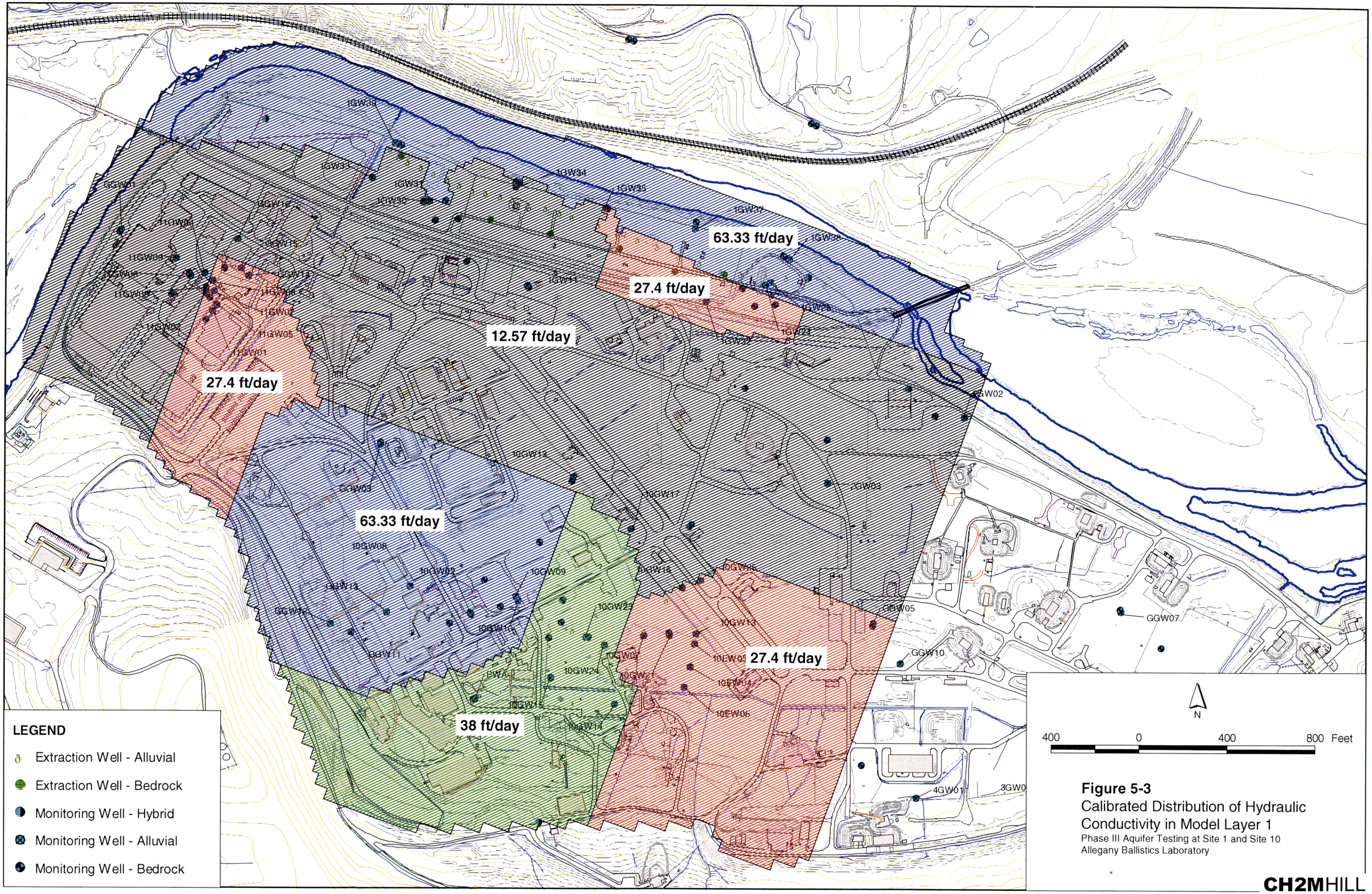
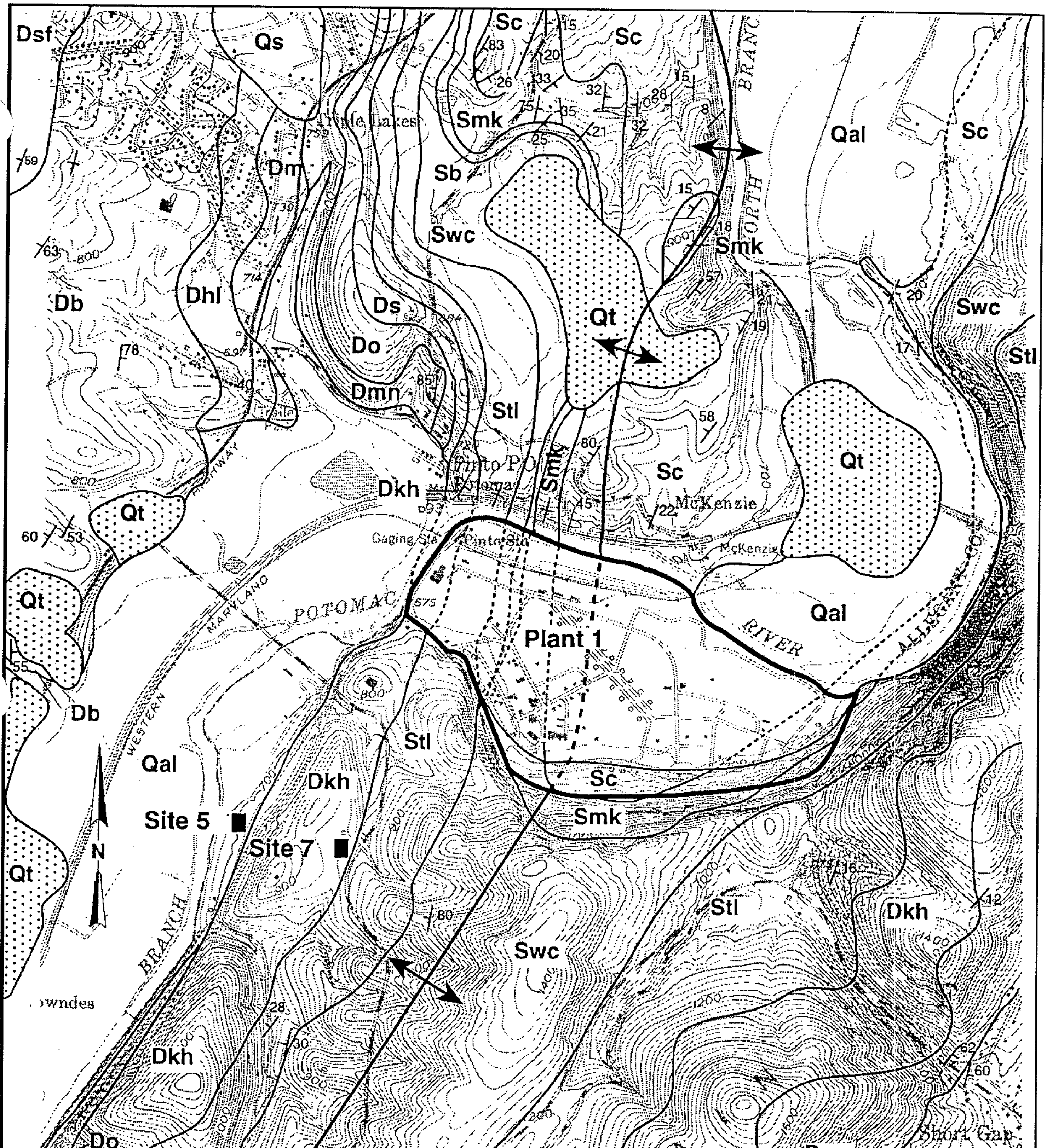


Figure 5-3
Calibrated Distribution of Hydraulic Conductivity in Model Layer 1
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory



Basemap: USGS 7.5 Minute Cresaptown, WV-MD quadrangle map.

0 1000 2000 3000
Scale in Feet

LEGEND

Location of Wills Mountain Anticlinal Axis, dashed where inferred (from Eddy, 1964)

63 Normal strike and dip

Vertical strike

Figure 5-4

Geologic Map of the Region Surrounding ABL

Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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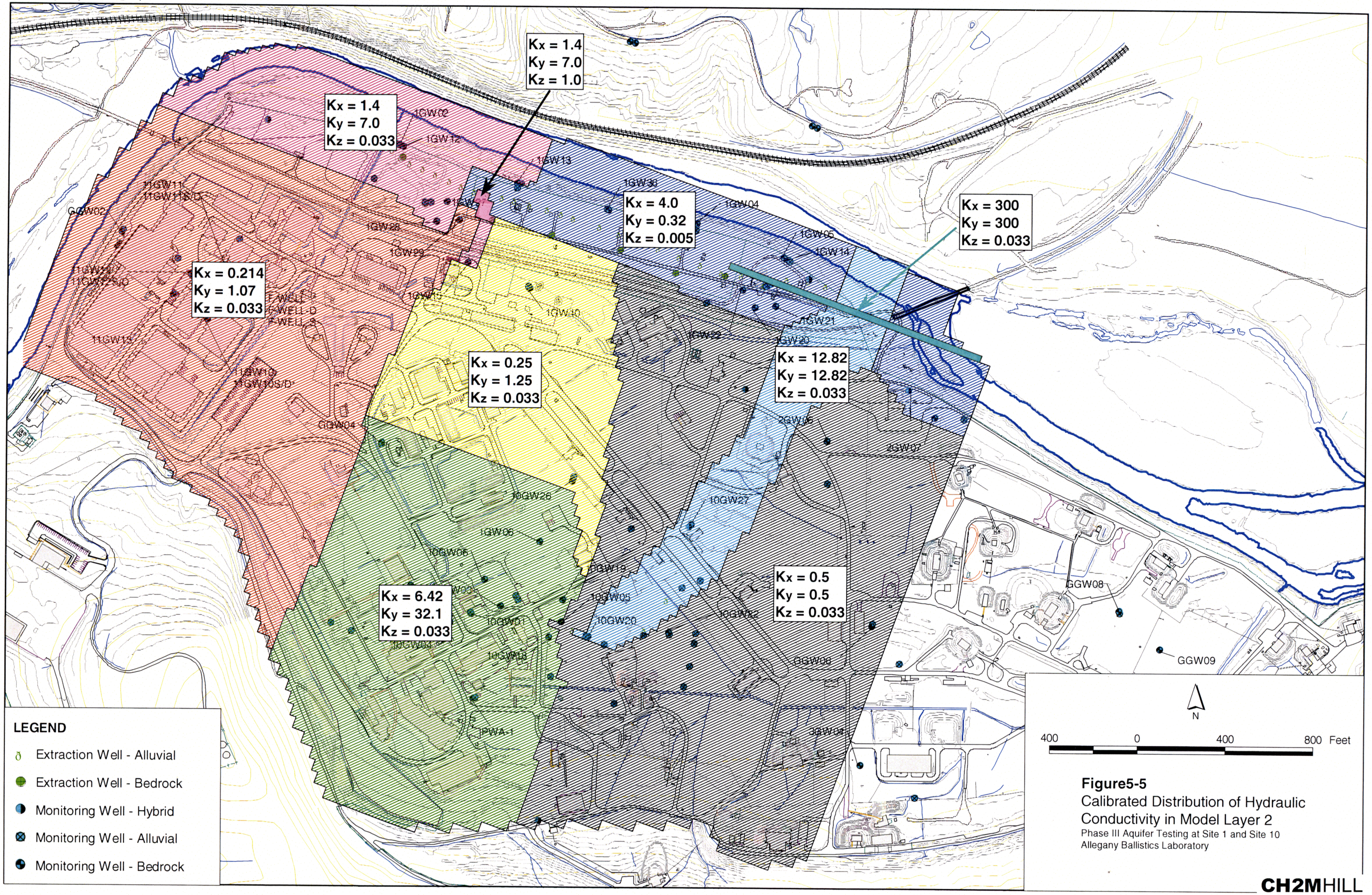

Figure5-5
Calibrated Distribution of Hydraulic Conductivity in Model Layer 2
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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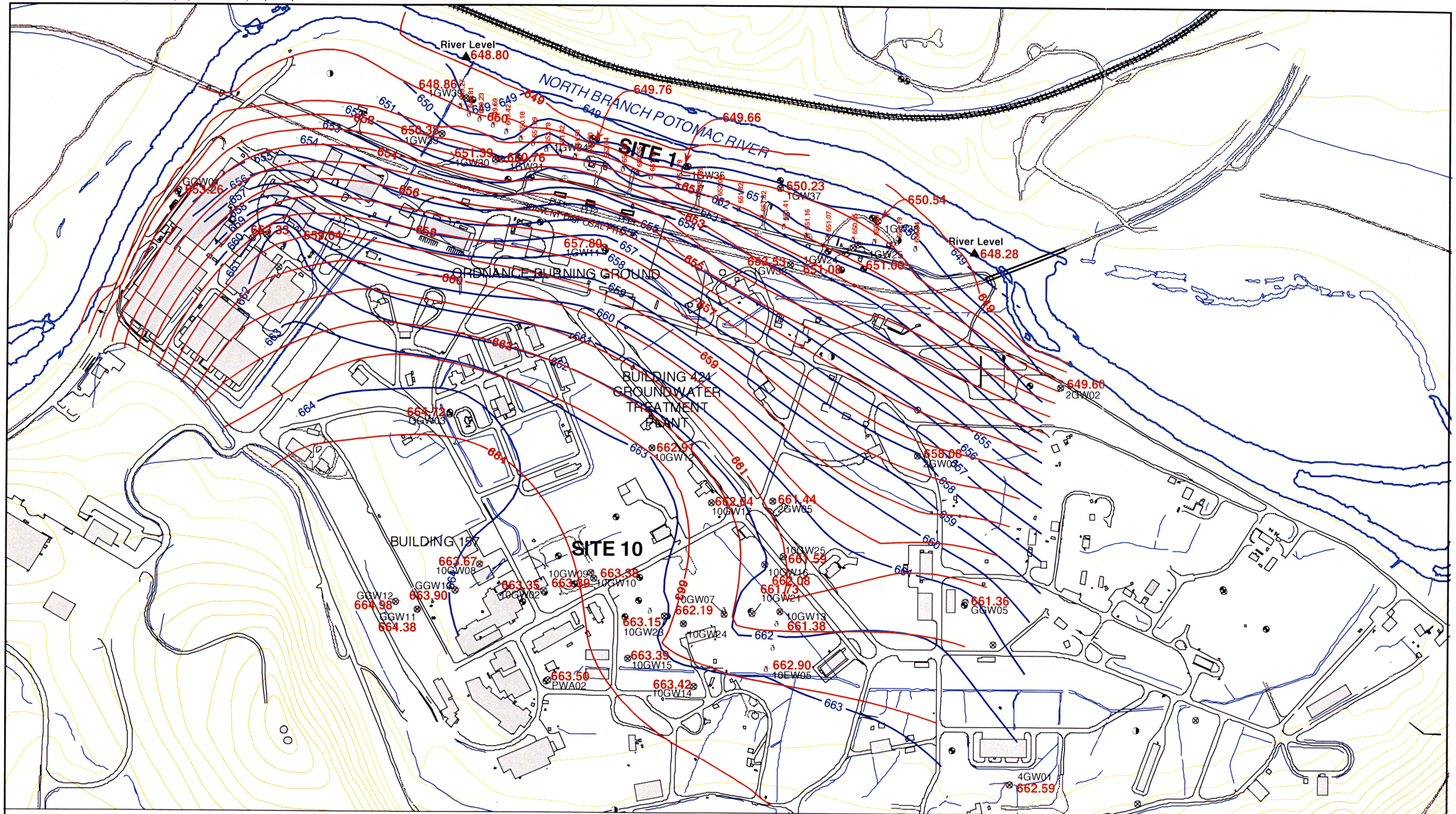

Legend

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Hybrid
- Monitoring Well - Alluvial
- Monitoring Well - Bedrock
- 663 Measured Water Level Contours
- 663 Simulated Water Level Contours
- 663.5 Measured Water Levels

N

400 0 400 800 Feet

Figure 5-6
Comparison of Measured and Simulated Water Levels for Non-Pumping Conditions in the Alluvial Aquifer, July 2, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistic Laboratory

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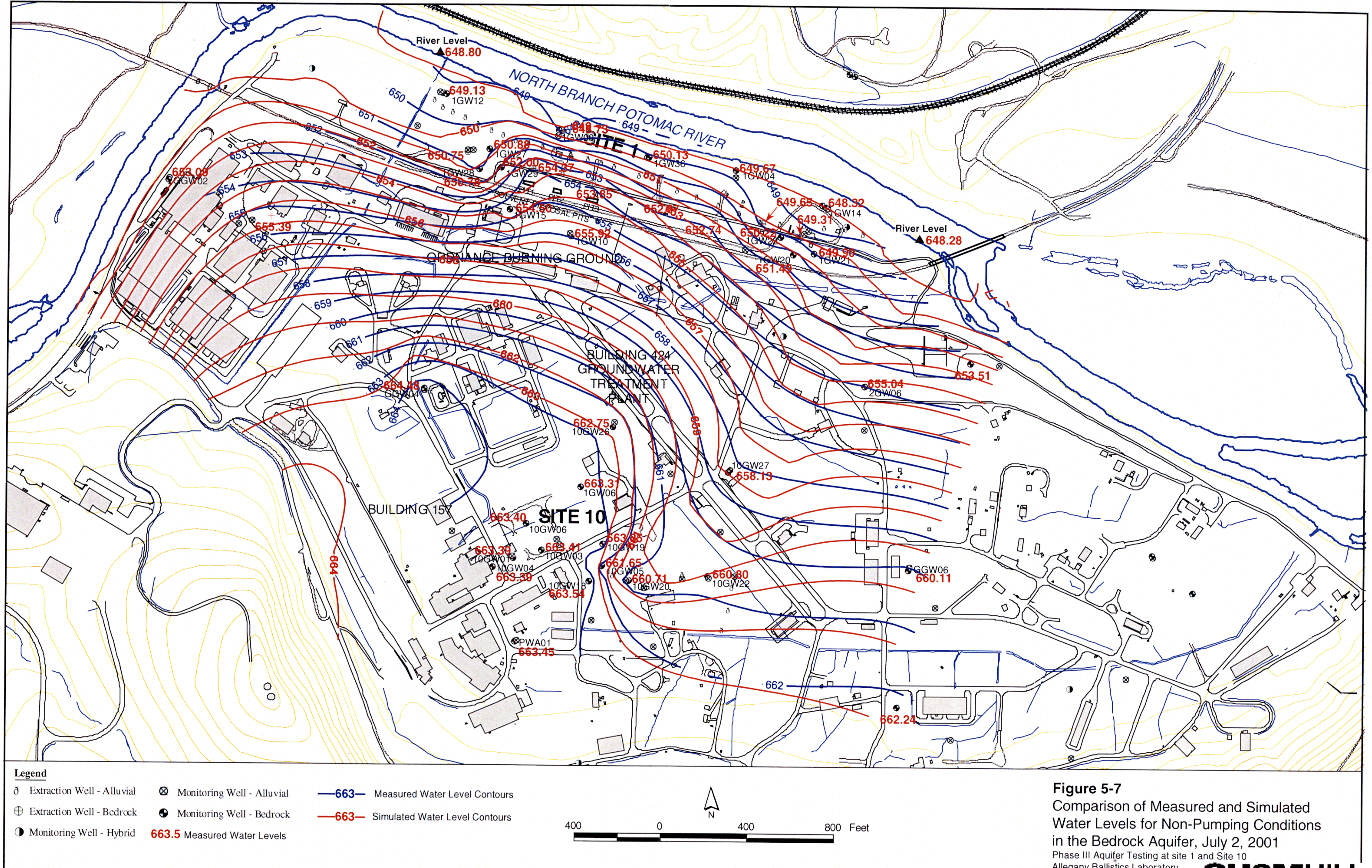

Figure 5-7
Comparison of Measured and Simulated Water Levels for Non-Pumping Conditions in the Bedrock Aquifer, July 2, 2001
Phase III Aquifer Testing at site 1 and Site 10
Allegany Ballistics Laboratory

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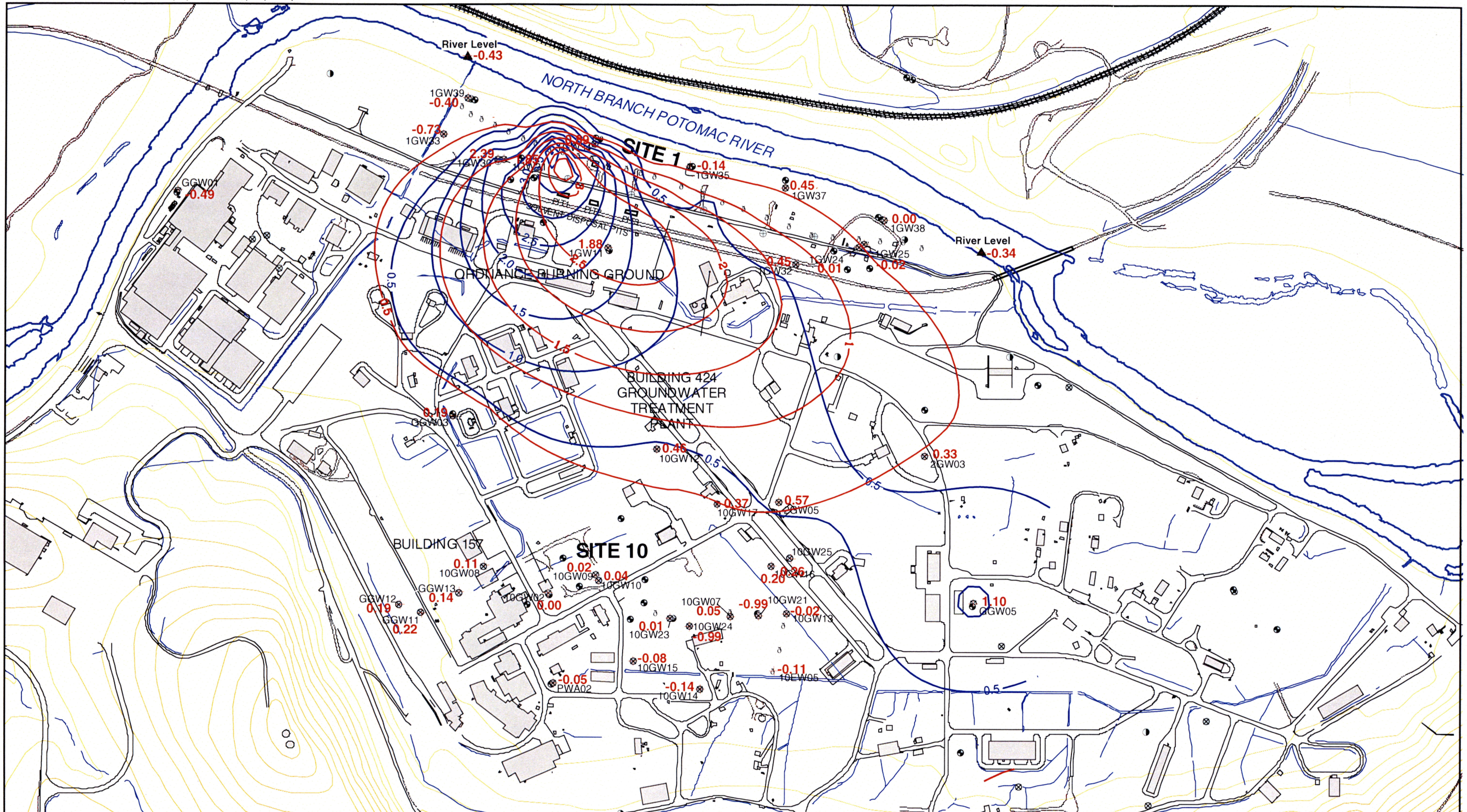

Legend

- Extraction Well - Alluvial
- Extraction Well - Bedrock
- Monitoring Well - Hybrid
- Monitoring Well - Alluvial
- Monitoring Well - Bedrock
- —1.00— Measured Drawdown Contours
- —1.00— Simulated Drawdown Contours
- 1.00 Measured Drawdown

N

400 0 400 800 Feet

Figure 5-8
Comparison of Measured and Simulated Drawdown in the Alluvial Aquifer During the Bedrock Pumping Test, July 2 to July 10, 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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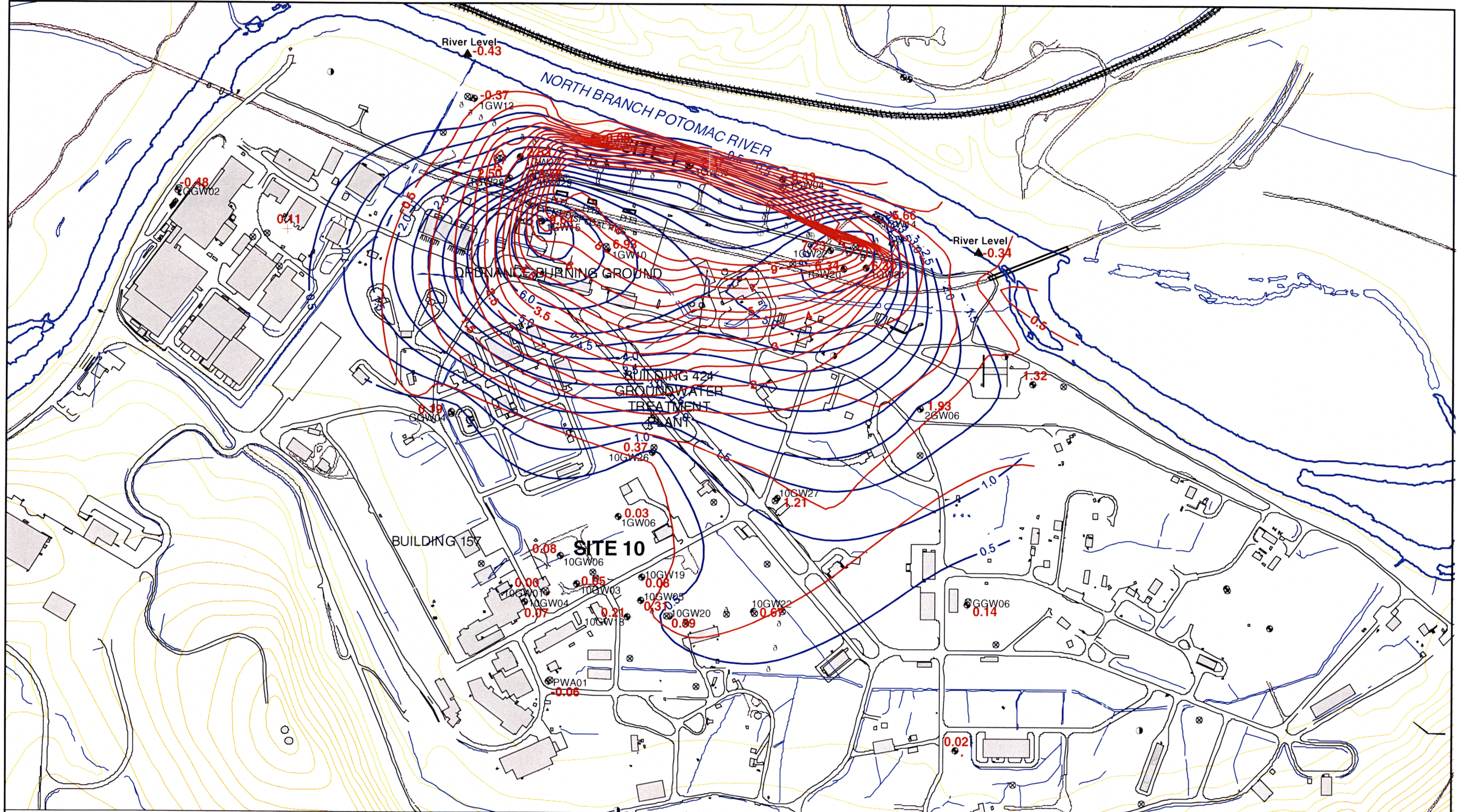

Legend

ϑ Extraction Well - Alluvial	⊗ Monitoring Well - Alluvial
⊕ Extraction Well - Bedrock	Monitoring Well - Bedrock
◑ Monitoring Well - Hybrid	1.00 Measured Drawdown

—1.00— Measured Drawdown Contours

—1.00— Simulated Drawdown Contours

N

400 0 400 800 Feet

Figure 5-9
Comparison of Measured and Simulated Drawdown in the Bedrock Aquifer During the Bedrock Pumping Test, July 2 to July 10, 2001

Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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6.0 Simulation of Bedrock Extraction at Site 10

6.1 Background

A groundwater extraction system consisting of three alluvial extraction wells has been operating at Site 10 since February 1999. Since the system was started up, a monitoring program of monthly water-level measurements has been used to evaluate the system's ability to control migration of TCE-contaminated groundwater at Site 10. The monthly monitoring has consistently shown that the three wells, 10EW35, 10EW36, and 10EW37, capture all of the alluvial TCE plume, except perhaps the extreme northeastern tip. To improve the reliability of the system in the northeastern corner of Site 10, a fourth alluvial extraction well (10EW38) was recently installed, but has not yet been put into service. Figure 6-1 shows the most recent alluvial TCE sampling results for Site 10 and the relationship between the current TCE plume and the extraction wells. The target plume for hydraulic containment is delineated by the estimated location of the 5 µg/l concentration contour.

Although there is some TCE contamination in the bedrock aquifer, the Site 10 remediation system was designed with extraction wells in the alluvium only. This decision was made because the TCE plume in the bedrock is smaller than the alluvial plume, and the data available when the system was being designed indicated that the drawdown produced by the alluvial extraction wells would increase the upward gradients in the plume area so that the system would capture both the alluvial and bedrock plumes. Figure 6-2 shows the most recent bedrock TCE sampling results, and outlines the estimated 5 µg/l plume boundary in the bedrock. Also, it was feared that extraction wells in the bedrock would cause downward gradients that might draw TCE downward from the larger alluvial plume, contaminating parts of the bedrock aquifer that would not otherwise be affected by TCE contamination.

Figure 6-3 shows the records of vertical head differences measured at three well pairs in the area of Site 10 affected by the alluvial and bedrock TCE plumes. The earliest measurements were collected from wells 10GW01 and 10GW02 in 1996 and early 1997. Those two wells are located in the western part of the TCE plume, and their early water-level data indicated upward flow. Later data were collected after groundwater remediation began and showed that the flow direction was more frequently downward.

Two additional pairs of monitoring wells, 10GW20/10GW23 and 10GW22/10GW21, were installed during construction of the Site 10 remediation system. They are located in the central and eastern parts of the TCE plume. Water-level data from those wells has consistently shown a strong potential for downward flow. The magnitude of the downward head differences in the central and eastern parts of Site 10 are greater than the drawdowns observed there during the pumping phase of the bedrock test. Therefore, while the operation of the Site 1 extraction wells probably increases the tendency for downward flow at Site 10, it is apparent that the downward gradients in the central and eastern parts of Site 10 occur naturally.

6.2 Simulation of Bedrock Extraction at Site 10

In response to the observation of generally downward hydraulic gradients in the TCE plume area at Site 10 and the influence of Site 1 bedrock pumping, it was decided that the Site 10 extraction system should be enhanced with the addition of extraction wells in the bedrock. The calibrated groundwater flow model was used to help select appropriate locations for bedrock extraction and to determine the pumping rates needed for plume capture. The evaluation of potential bedrock extraction wells was guided by the following considerations:

- The productivity of new wells installed in the bedrock is difficult to predict because it depends on the nature of the fractures intersected by the well, if any. Therefore, it is preferable to convert existing monitoring wells of known productivity rather than to take the chance of installing new extraction wells that may not produce the needed flow.
- To the extent possible, bedrock extraction wells should capture the areas currently occupied by the bedrock TCE plume without spreading the plume into areas not currently contaminated.
- Pumping in the bedrock will increase the natural tendency for downward flow in the Site 10 plume area. Therefore, the bedrock extraction wells must be capable of capturing any contamination that may be drawn down into the bedrock under the footprint of the alluvial TCE plume.

To address these design considerations, the groundwater flow model was used to evaluate the hydraulic capture zones produced by pumping at several alternative combinations of existing Site 10 bedrock wells. All of the bedrock monitoring wells were constructed as six-inch open-hole wells cased through the alluvium. This is the same construction that was used for the bedrock extraction wells installed at Site 1. Therefore, any of the Site 10 monitoring wells could be converted for use as extraction wells. The main questions in selecting wells for conversion are their locations with respect to the alluvial and bedrock TCE plumes and the productivity of the wells.

Productivity concerns were addressed by testing the yield of the monitoring wells that appeared to be good candidates for conversion because of their locations. Yield tests were run by pumping each well for 30 minutes to 1 hour at the maximum rate that could be sustained at a stabilized drawdown. Table 6-1 lists the productivity estimates for selected Site 10 bedrock wells as determined by yield testing. The table also shows the test result for the new alluvial extraction well 10EW38. Well 10EW38 is not yet in operation, but was included in simulations of the enhanced Site 10 extraction system.

6.2.1 Hydraulic Capture Analysis

6.2.1.1 Particle Tracking

Hydraulic capture of the alternative configurations of enhanced extraction systems was evaluated by particle-tracking simulations using the post-processing programs MODPATH and MODPATH-PLOT (Pollock, September 1994). These computer codes were developed by the U. S. Geological Survey for visualization of the simulated flow fields generated by the MODFLOW groundwater modeling code. Pathlines of groundwater flow are visualized by injecting imaginary water particles into the flow field and tracing their trajectories as determined by the flow vector components produced as output by MODFLOW. The particle tracking technique is essential as a tool for delineating capture zones at Site 10 because the flow is three-dimensional and the bedrock is horizontally anisotropic. Because of the horizontal anisotropy, flow lines are not necessarily orthogonal to the simulated equipotentials. The particle tracking post-processor, however, uses the vector components of the simulated flow and does not assume orthogonality of pathlines and equipotentials.

6.2.1.2 Particle Injection

The particle-tracking analysis of bedrock extraction wells at Site 10 used three sets of particles that were injected in the Site-10 plume areas and tracked in the direction of flow to their ultimate point of discharge. Captured particles were drawn into the Site 10 extraction wells. Uncaptured particles escaped from Site 10 and discharged to the extraction wells at Site 1. No cases were observed where particles escaping from Site 10 discharged to the North Branch Potomac River.

Each set of particles was injected in a uniformly-spaced pattern with particles on 50-foot centers covering an area of the same size and shape as the TCE plume. One set of particles was released at an elevation corresponding to the middle of the saturated alluvial aquifer over an area corresponding to the alluvial TCE plume shown in Figure 6-1. A second set of particles was released at a depth of 50 feet below the top of bedrock over an area corresponding to the bedrock TCE plume shown in Figure 6-2. These two particle sets represent known areas of TCE contamination in the alluvium and bedrock. The third set of particles was released at the top of the bedrock aquifer over an area covering the footprint of the alluvial TCE plume. These particles represent potential contamination in the upper bedrock aquifer that could result from increased downward flow caused by pumping the bedrock extraction wells.

Figure 6-4 shows a the results of a particle-tracking simulation of the current groundwater remediation system. The simulated extraction wells in this simulation include 27 alluvial and 7 bedrock extraction wells at Site 1 and 4 alluvial extraction wells at Site 10. (Well 10EW38 is included in the simulation because its addition to the Site 10 system is not contingent on the results of this modeling). The simulation shows that some particles from the bedrock TCE plume escape Site 10 under the current configuration, but are captured by the Site 1 extraction system. Particles from the alluvial TCE plume are all contained at Site 10.

To prevent contaminant escape from Site 10, several different combinations of bedrock extraction wells were simulated and evaluated by particle tracking. Some combinations of wells were able to provide complete hydraulic capture of the injected particles at pumping rates lower than the tested productivity of each well. Three of the successful combinations are illustrated in the following examples.

6.2.3 Hydraulic Capture with Bedrock Wells 10GW01, 10GW03, and 10GW27

Figure 6-5 shows the particle tracking results of a simulation in which three existing bedrock monitoring wells were converted for extraction and used in combination with the four existing alluvial extraction wells at Site 10. The figure shows the simulated pumping rates of all extraction wells. The total simulated pumping rates at Site 10 were 45 gpm for the four alluvial extraction wells and 37 gpm for the three proposed bedrock wells. Each of the simulated extraction wells has been yield-tested at rates higher than the simulated pumping rate. Although they are not shown, the alluvial and bedrock extraction wells at Site 1 were simulated at a total pumping rate of 105 gpm, which is a typical rate for the Site 1 wells.

The particle tracks in Figure 6-5 are color-coded so that capture of the alluvial plume, the bedrock plume, and the potential future contamination at the top of bedrock can be distinguished. The blue particle tracks show the paths of particles released in the alluvial TCE plume. Most of them were captured by alluvial extraction wells, but some were transported downward into the bedrock and captured by well 10GW27.

The green particle tracks represent particles released in the bedrock TCE plume. All of the bedrock particles were captured, but many were drawn to the northeast beyond the area of the current bedrock plume, where they were captured by well 10GW27.

The red Lines in Figure 6-5 are the tracks of particles started at the top of the bedrock aquifer in an area corresponding to the footprint of the alluvial TCE plume. Some of these particles were captured by alluvial extraction wells, but most migrated downward and were captured by bedrock wells.

As shown in Figure 6-5, all of the particles started in the current TCE plumes and in the bedrock footprint of the alluvial plume were captured by this system of four alluvial and three bedrock wells. The main drawback to this system is that some particles were drawn outside of the current plume areas to well 10GW27 before being captured.

6.2.4 Hydraulic Capture with Bedrock Wells 10GW01, 10GW03, and PWC

Figure 6-6 shows capture of the TCE plumes by the four existing alluvial extraction wells supplemented by a three-well bedrock extraction system consisting of wells 10GW01, 10GW03, and PWC. Well PWC is a former bedrock production well that has not been used for water supply for several years because of groundwater contamination detected there. It is in an advantageous position near the northeastern edge of the bedrock TCE plume. As Figure 6-6 shows, the use of well PWC instead of 10GW27 can provide hydraulic containment at the same pumping rate. It has the advantage of producing a more compact capture zone that does not draw contamination as far to the northeast before capturing it.

The hydraulic characteristics of well PWC are not presently known, but it is believed to be 300 feet deep. Because it was used as a production well, it can probably be pumped at a relatively high rate. However, it is possible that much of the well's productivity is derived from the deep bedrock. It would not be desirable to draw contaminants downward to greater depths than necessary during remediation. Therefore, a program of packer testing is proposed to determine where the majority of the water enters the well and how productive it is at depths of 90 feet and less.

6.2.5 Hydraulic Capture with Bedrock Wells 10GW01, 10GW03, 10GW19, and PWC

Figure 6-7 shows capture of the TCE plumes by a system that uses four extraction wells in the bedrock. One advantage of this system is that it produces an even more compact bedrock capture zone than the system of Figure 6-6. Furthermore, the individual wells in the four-well system are pumped at slightly lower rates, so that this system is more robust.

Although the groundwater model used in these simulations was carefully calibrated, there is still some uncertainty about the hydraulic properties and the response of the bedrock to new pumping. With the four-well system in the bedrock, the pumping rates can be increased if future monitoring shows less capture effectiveness than was indicated by the model.

Comparison of Figures 6-6 and 6-7 shows that the four-well bedrock system captures the bedrock TCE plume, represented by the green particles, in a smaller area than the three-well system of Figure 6-6. The red particle tracks, however, appear to be more tightly contained by the three-well system. That is because wells 10GW01 and 10GW03 were pumped at higher rates and there was no competition from well 10GW19 when only three bedrock wells were used. The red particles represent potential future contamination at the top of the bedrock that may not actually occur. Consequently, the four-well system's advantages with respect to known bedrock contamination probably out-weigh its slightly poorer performance with respect to hypothetical future contamination.

Because the four-well system of Figure 6-7 utilizes production well PWC, it will be necessary to investigate the properties of that well before proceeding with this bedrock extraction option.

6.3 Monitoring Requirements

Performance monitoring of the current alluvial extraction system at Site 10 is done primarily by monthly water-level measurements in the Site 10 alluvial monitoring wells. The alluvial network of monitoring wells includes some wells that have been installed specifically to provide water-level data in critical locations for demonstrating hydraulic capture.

When bedrock extraction wells are added to the Site 10 remediation system, the bedrock monitoring network will need to be improved so that hydraulic containment in the bedrock can be demonstrated. Because some areas of the bedrock are believed to be anisotropic, analysis of the capture zones there is more difficult than in the alluvial aquifer. To assist in designing a suitable bedrock monitoring network, simulations with the groundwater flow model were used to evaluate the usefulness of different monitoring locations.

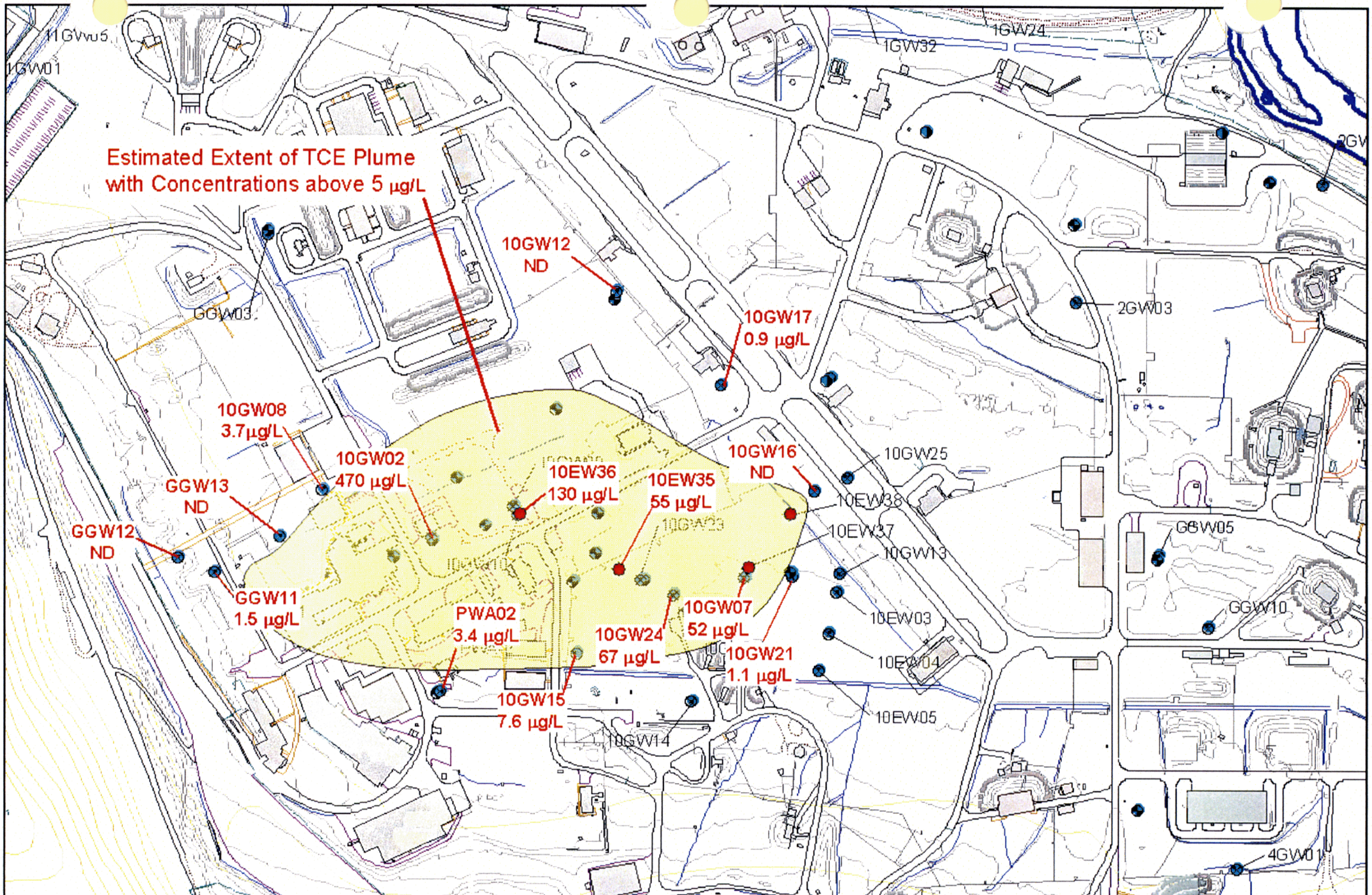
Assuming that the four-well bedrock extraction option will be installed, the model was used to investigate the differences in the potentiometric surface corresponding to complete hydraulic capture of the bedrock plume and incomplete capture. Figure 6-8 shows a contour map of the bedrock potentiometric surface for a situation of incomplete hydraulic capture, as indicated by the escaping green bedrock particle tracks. Figure 6-9 shows the same map in a situation of complete hydraulic capture. The contours show that there is a flow divide approximately 60 feet northeast of well PWC, and that currently there are no bedrock monitoring wells in that area. Both figures show the locations of two proposed new monitoring wells necessary to detect hydraulic containment in the area where the potential for escape is greatest. They also show the simulated water levels at those wells for the two different flow conditions. In both cases, the difference in the simulated water levels is small, but measurable. In Figure 6-9 the difference in the simulated water levels indicates a southwesterly flow toward well PWC and a closed bedrock capture zone. In Figure 6-8, the simulated water levels indicate that flow in the critical area between the wells has not been reversed, and that hydraulic capture is incomplete.

The simulation results presented in figures 6-8 and 6-9 show that two new bedrock monitoring wells would be needed if the four-well bedrock extraction system is installed. If another bedrock extraction option is chosen, new monitoring well locations will have to be chosen. However, it is likely that two additional monitoring wells would be adequate.

It is noteworthy that Figure 6-9 shows bedrock capture for the four-well extraction system at a bedrock pumping rate of 31 gpm, while Figure 6-7 shows that 36 gpm is needed for complete hydraulic capture. The difference is that pumping at 31 gpm achieves capture of the existing bedrock plume but only incomplete capture of the hypothetical future contamination at the top of the bedrock. Design of the potentiometric monitoring network in the bedrock should be based on demonstration of bedrock capture. Capture of contaminants flowing vertically between aquifers is a three-dimensional phenomenon that is not effectively addressed by hydrodynamic monitoring. If this situation arises, it will probably only be detected by long-term water quality monitoring.

Table 6-1
Yield Test Results for Selected Site-10 Wells
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

Well	Yield (gpm)
10GW01	14.5
10GW03	10
10GW04	35
10GW06	14
10GW18	<3
10GW19	7
10GW20	8
10GW27	20
10EW38	12



LEGEND

Alluvial Monitoring Well

Hybrid Monitoring Well

Bedrock Monitoring Well

Alluvial Extraction Well

Figure 6-1
TCE Plume in the Alluvial Aquifer at Site 10
Based on Sampling Results for April 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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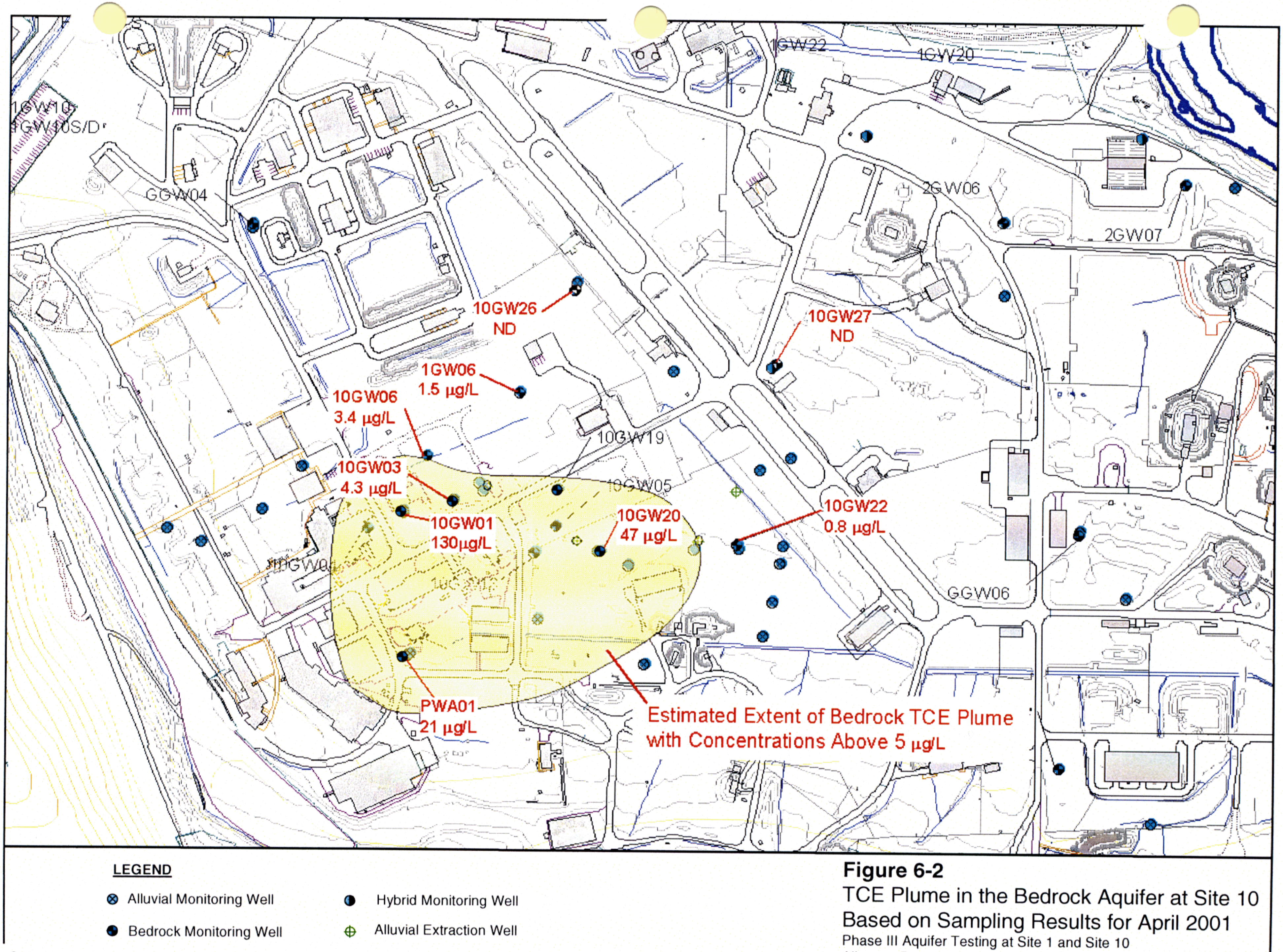

Figure 6-2
TCE Plume in the Bedrock Aquifer at Site 10
Based on Sampling Results for April 2001
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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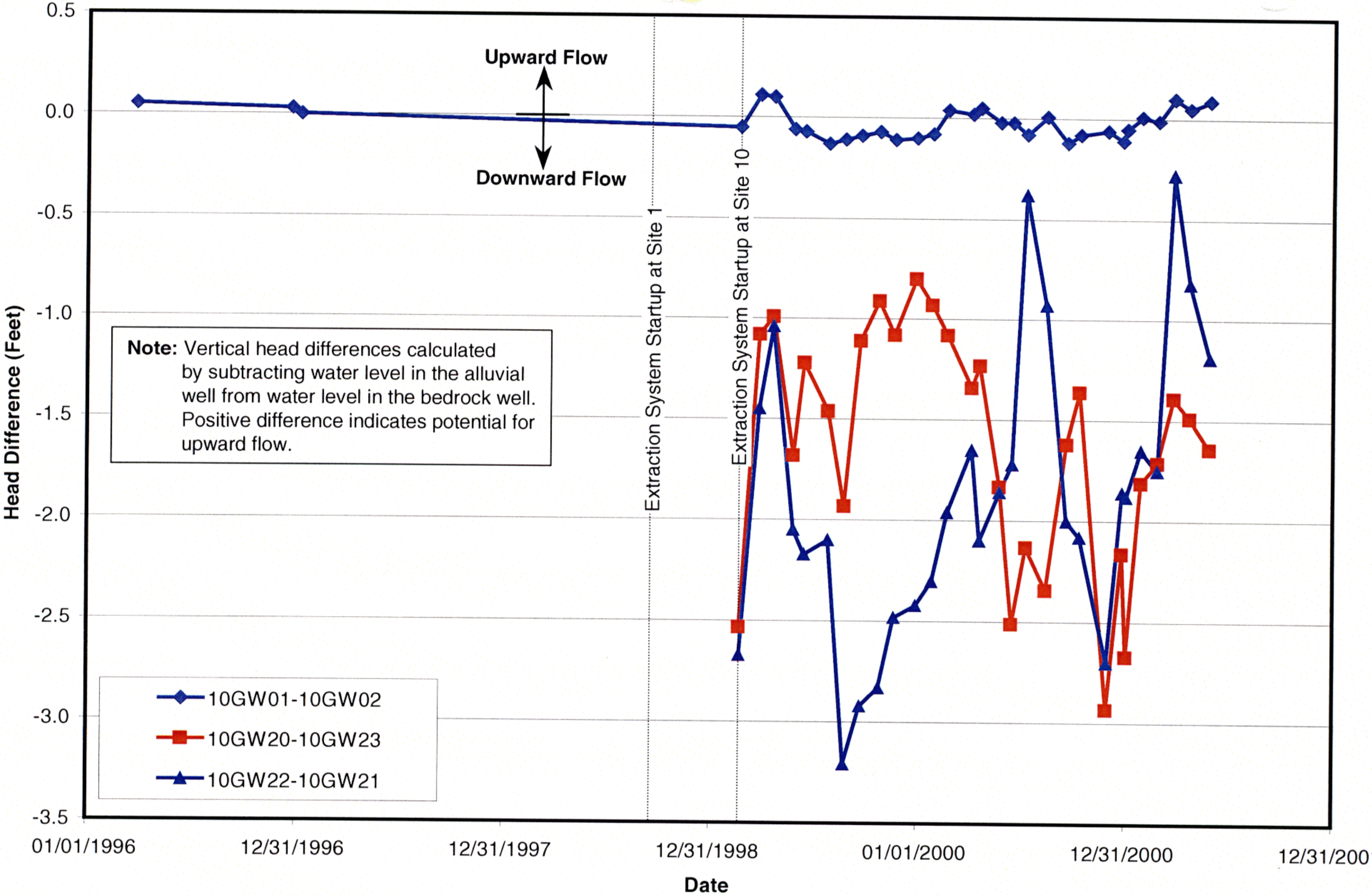

Figure 6-3
Records of Vertical Head Differences
at Three Site-10 Monitoring Well Clusters
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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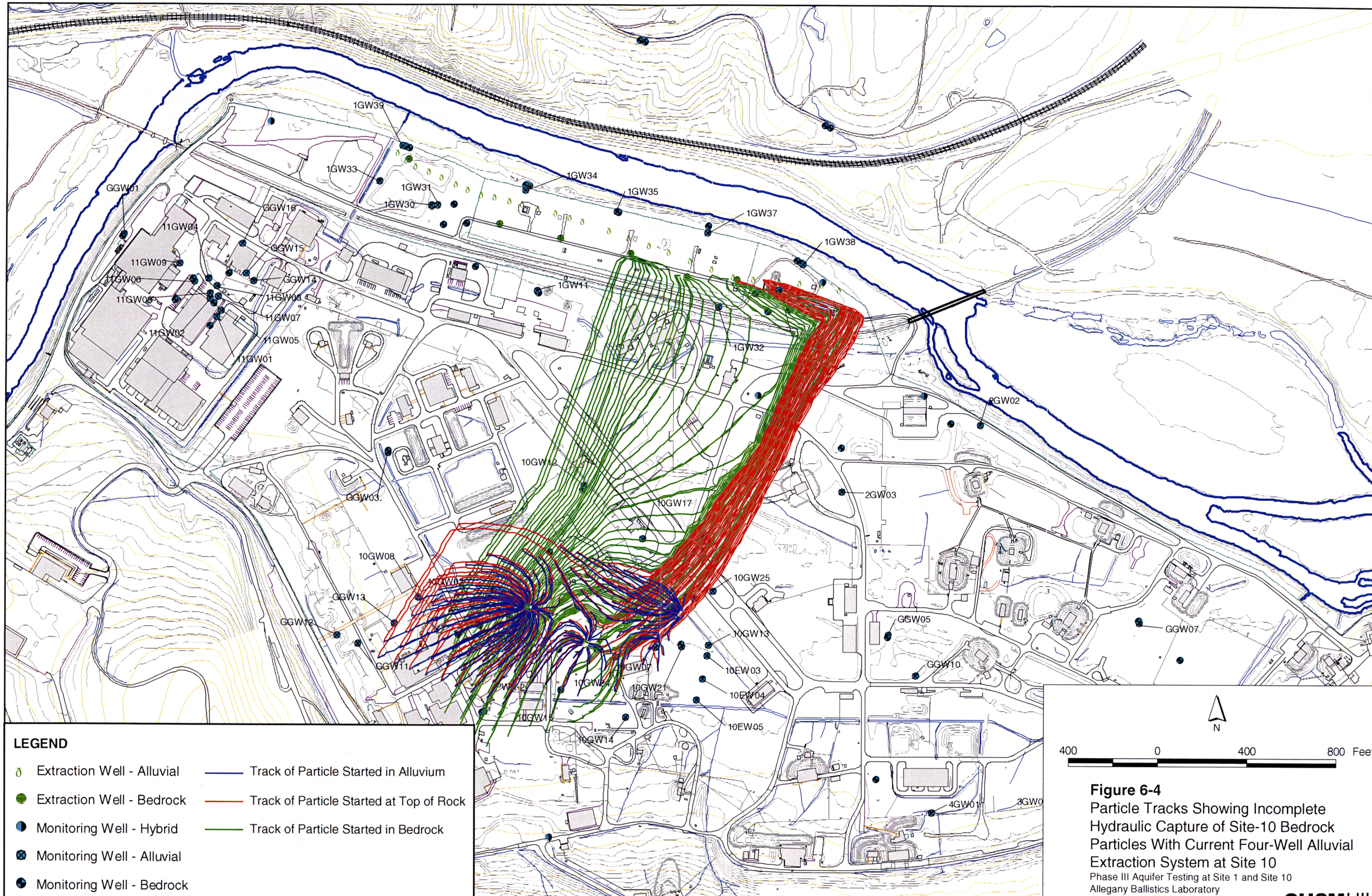

Figure 6-4
Particle Tracks Showing Incomplete Hydraulic Capture of Site-10 Bedrock Particles With Current Four-Well Alluvial Extraction System at Site 10
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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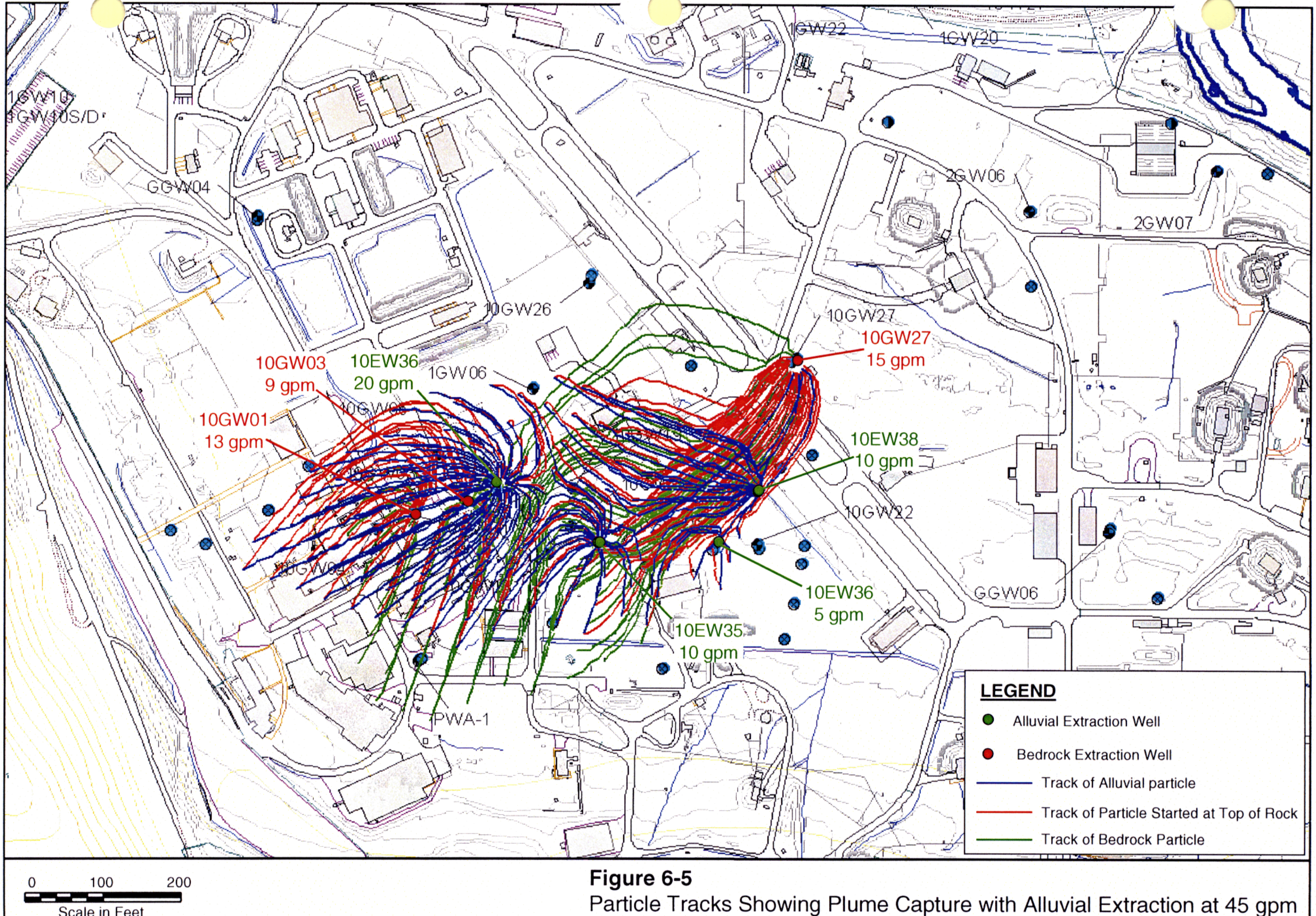

Figure 6-5
Particle Tracks Showing Plume Capture with Alluvial Extraction at 45 gpm and Bedrock Wells 10GW01, 10GW03, and 10GW27 Pumping 37 gpm
Phase III Aquifer Testing at Site 1 and site 10
Allegany Ballistics Laboratory

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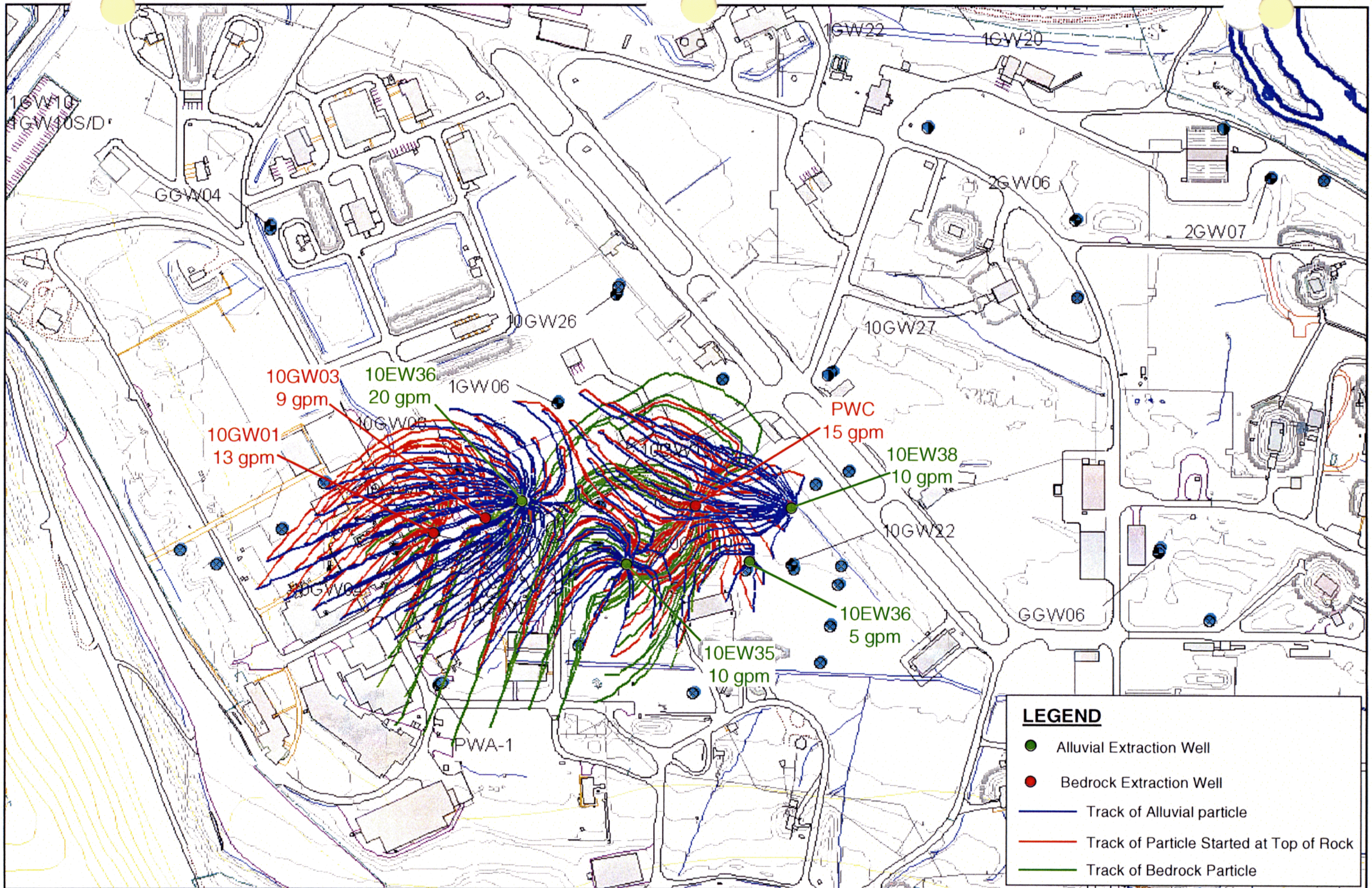

Figure 6-6
Particle Tracks Showing Plume Capture with Current Alluvial Extraction and Bedrock Wells 10GW01, 10GW03, and PWC Pumping 37 gpm
Phase III Aquifer Testing at Site 1 and site 10
Allegany Ballistics Laboratory

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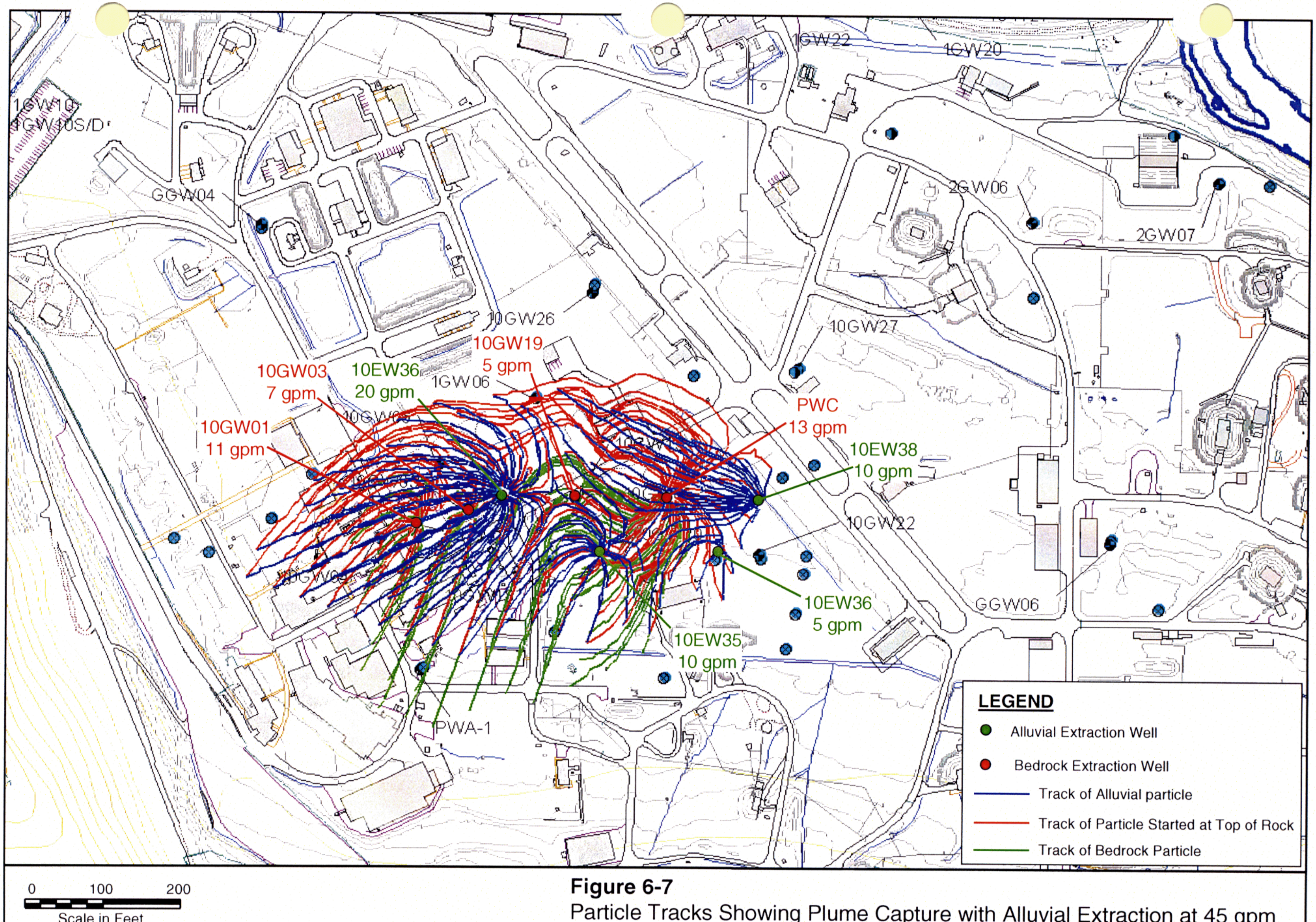

Figure 6-7
Particle Tracks Showing Plume Capture with Alluvial Extraction at 45 gpm and Bedrock Wells 10GW01, 10GW03, 10GW19 and PWC Pumping 36 gpm
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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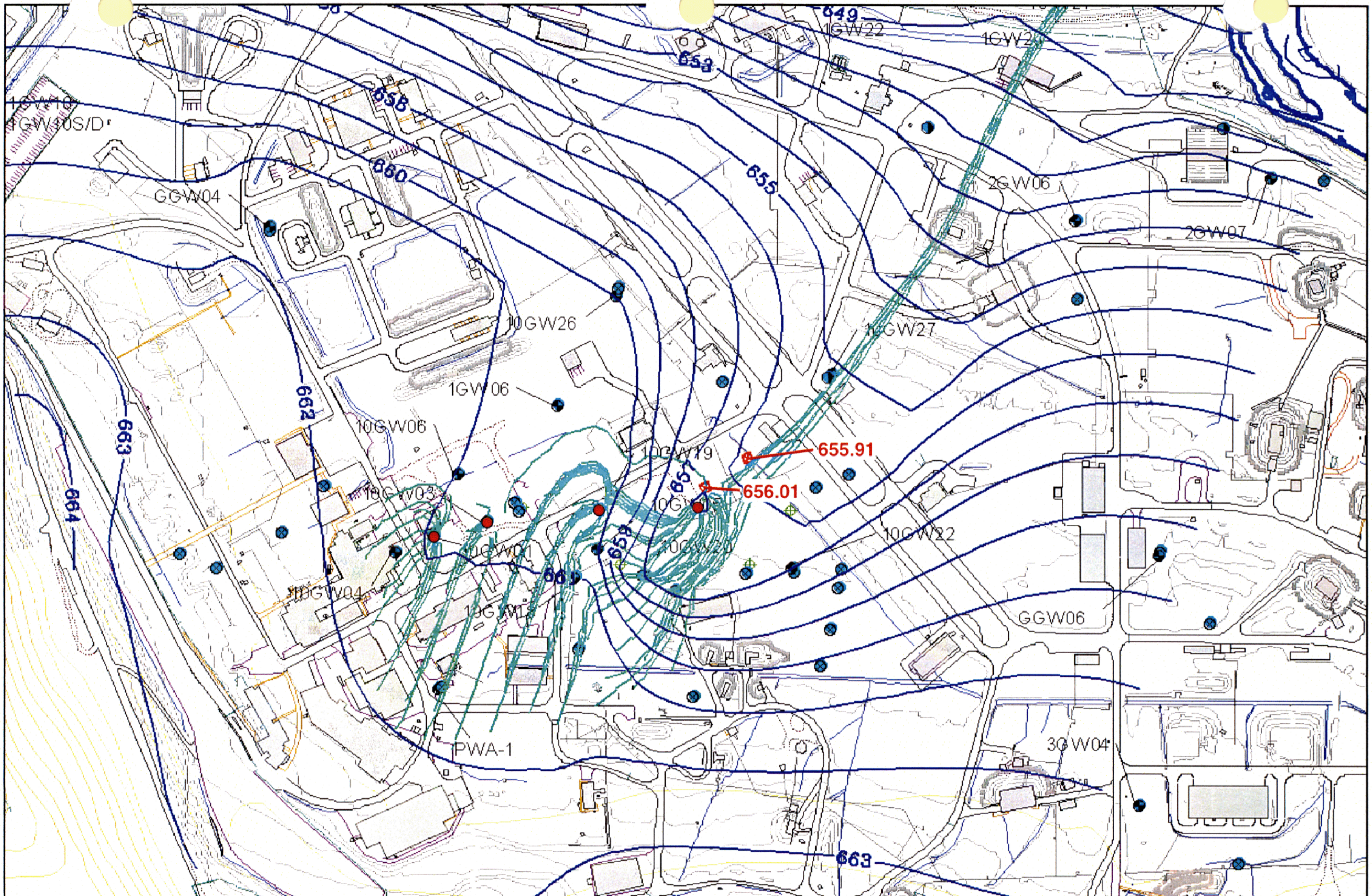

Legend

- Existing Alluvial Monitoring Well
- Existing Bedrock Monitoring Well
- New Bedrock Monitoring Well
- Simulated Equipotential
- Bedrock Particle Track

Figure 6-8
Simulated Water Levels at Proposed New Bedrock Monitoring Wells with Incomplete Capture at 25 gpm
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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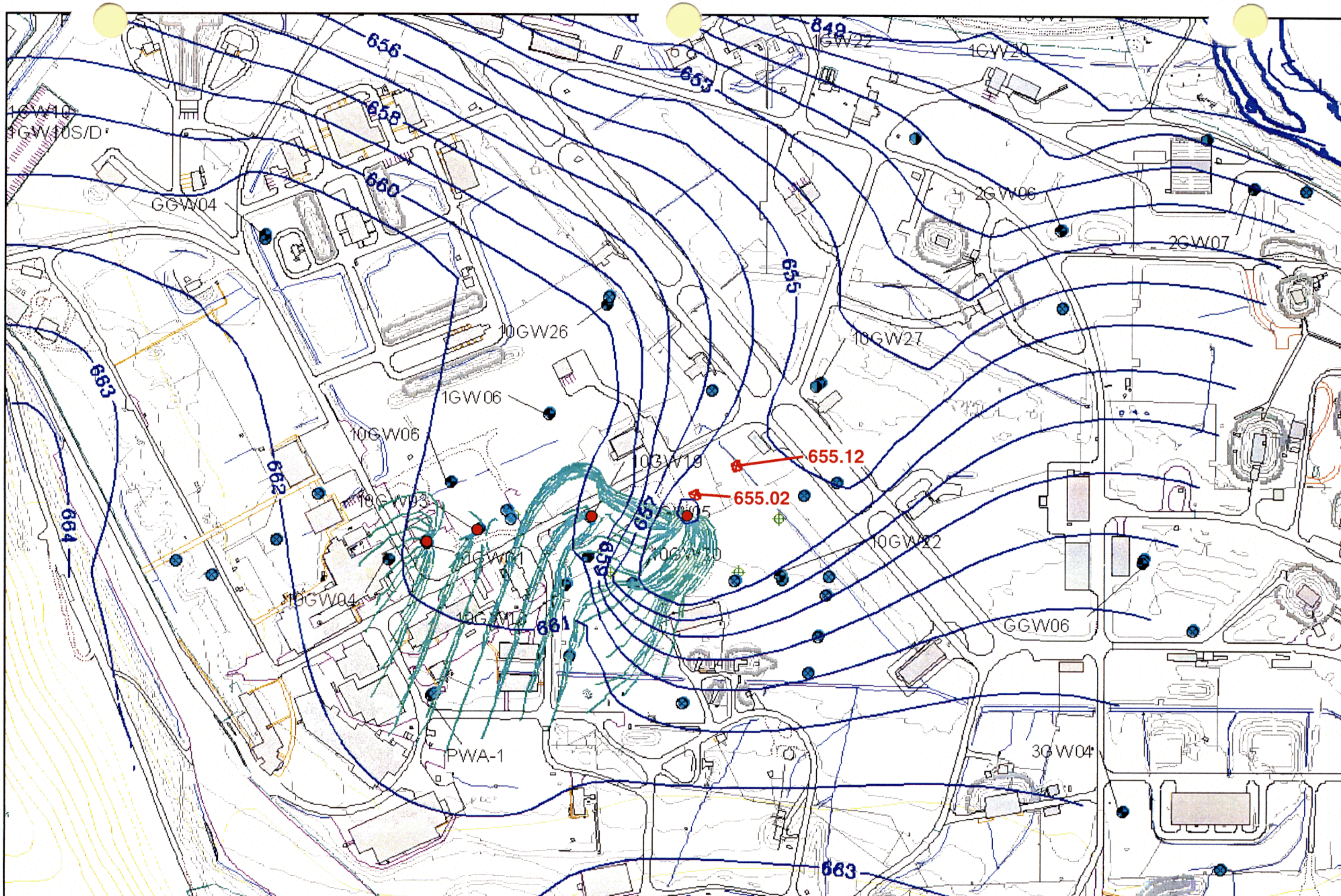

0 100 200
Scale in Feet

Legend
- Existing Alluvial Monitoring Well
- Existing Bedrock Monitoring Well
- New Bedrock Monitoring Well
- Simulated Equipotential
- Bedrock Particle Track

Figure 6-9
Simulated Water Levels at Proposed New Bedrock Monitoring Wells with Hydraulic Capture at 31 gpm
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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Appendix A — Drilling and Well Installation

This appendix describes the drilling and well installation procedures used during Phase III Aquifer Testing. Two alluvial extraction wells, four alluvial monitoring wells, one bedrock extraction well, and four bedrock monitoring well were installed at Site 1 and Site 10.

A-1 Drilling Methods

Three drilling methods were used to install the extraction wells and monitoring wells during the Phase III Aquifer Testing: (1) rotasonic drilling, (2) air hammer drilling, and (3) air hammer drilling with simultaneous casing advancement .

The rotasonic drilling method utilizes a combination of hydraulic pressure and mechanically generated oscillations to advance a dual line of drill pipe. The drill head transmits hydraulic and vibratory power directly to the dual line of pipe. The inner pipe represents the core barrel sampler while the outer pipe is used to prevent collapse of the borehole and in construction of monitoring and extraction wells. Once the inner pipe reaches the desired depth, the outer drill pipe is advanced down over the inner pipe. The inner pipe is then lifted to the ground surface for core recovery. The borehole is widened to the desired diameter by advancing a series of successively larger diameter pipes over one another. This method advances drilling pipe into consolidated and unconsolidated material without the use of water, mud, or air.

The air hammer drilling method uses air-powered hammering action to pulverize the subsurface material which is removed from the borehole by the release of compressed air. This method cannot be used alone within the overburden at ABL, as the unconsolidated overburden material tends to collapse into the borehole. Therefore, the air hammer drilling method was used with simultaneous steel casing advancement to drill through the overburben at ABL. In this method, the air hammer is designed such that when it is lowered through the inside of the steel casing, a lip on the hammer catches on another lip on the bottom of the casing. This allows only the lower portion of the hammer to extend beyond the bottom of the casing. As the hole is advanced, clockwise rotation of the drilling stem causes the bottom portion of the hammer to swing out and drill a hole slightly larger than the diameter of the steel casing. The hammering action generated on the bottom lip of the casing causes it to advance as the hole is drilled through the overburden and into bedrock. The hammer is removed by rotating the drilling stem counterclockwise to close the hammer and then withdrawing the drilling stem from the inside of the casing. The steel casing then acts as a temporary restraining wall for the overburden while a well or surface casing is installed.

A-2 Well Installation and Construction Procedures

This section describes the specific drilling technique and well construction details for each monitoring well and extraction well installed during Phase III Aquifer Testing. Drilling services for the well installations were provided by various drilling subcontractors while inspection and supervision of the drilling activities were provided by CH2M HILL. Surveying services for all wells were provided by Chapman Surveyors of Cumberland, Maryland.

A-2.1 Site 1 Wells

1EW35

Well 1EW35 is an experimental bedrock extraction well that was installed by Eichelbergers in July 2000. Air hammer drilling with simultaneous casing advancement was used to install a 10-inch-diameter steel surface casing to a depth of 38.5 feet bgs (i.e., approximately one-half foot into bedrock). Once the grout around the surface casing set up, air hammer drilling was used to advance an open borehole to a depth of 65 feet bgs. A significant water-bearing fracture in the bedrock was noted at a depth from 58 to 59 feet bgs.

1GW02

Well 1GW02 was an existing monitoring well that was overdrilled and modified into an open borehole bedrock well by Eichelbergers. In March 2001, the modification of 1GW02 began by removing the existing PVC casing and screen and reaming the borehole. Almost immediately upon the start of reaming, it was discovered that the surface casing only extended to about 3 feet bgs. Therefore, in order to convert this well to standard bedrock well construction, a 6-inch diameter surface casing was installed to 37 feet bgs (i.e. about 3 feet into competent bedrock) using air hammer drilling with simultaneous casing advancement. Once the grout around the surface casing set up, an open borehole was advanced in approximately 5-foot intervals until a final depth of 80 feet was attained.

A-2.2 Site 10 Wells

10EW37

Well 10EW37 is an alluvial extraction well that was installed by Alliance Environmental in July 1998. Rotasonic drilling was used to advance the borehole to the top of bedrock (i.e., about 15 feet bgs). The well was constructed of 10 feet of 6-inch-diameter stainless steel 0.02-inch slot screen (from 5 to 15 feet bgs) and 6-inch-diameter Schedule 80 PVC riser to the ground surface. The well was finished with a temporary flush-mount protective casing until it is converted to an active extraction well.

10EW38

Well 10EW38 is an alluvial extraction well that was installed by Eichelbergers in July 2000. Air hammer drilling with simultaneous casing advancement was used to advance the borehole to the top of bedrock (i.e., about 19 feet bgs). The well was constructed of 5 feet of 6-inch-diameter Schedule 80 PVC 0.02-inch slot screen (from 14 to 19 feet bgs) and 6-inch-diameter Schedule 80 PVC riser to the ground surface. The well was finished with a temporary flush-mount protective casing until it is converted to an active extraction well.

10GW21

Well 10GW21 is an alluvial monitoring well that was installed by Alliance Environmental in July 1998. Rotasonic drilling was used to advance the borehole to the top of bedrock (i.e., about 15 feet bgs). The well was constructed of 10 feet of 2-inch-diameter Schedule 40 0.01-inch slot screen (from 5 to 15 feet bgs) and riser.

10GW22

Well 10GW22 is a bedrock monitoring well that was installed by Alliance Environmental in July 1998. Rotasonic drilling was used to advance the borehole to approximately 10 feet into competent bedrock and install an 8-inch-diameter steel surface casing to a depth of 28 feet bgs. Once the grout around the surface casing set up, air hammer drilling was used to advance an open borehole to a depth of 90 feet bgs.

10GW23

Well 10GW23 is an alluvial monitoring well that was installed by Alliance Environmental in July 1998. Rotasonic drilling was used to advance the borehole to the top of bedrock (i.e., about 22 feet bgs). The well was constructed of 10 feet of 2-inch-diameter Schedule 40 0.01-inch slot screen (from 12 to 22 feet bgs) and riser.

10GW24

Well 10GW24 is an alluvial monitoring well that was installed by Alliance Environmental drilling subcontractor in July 1998. Rotasonic drilling was used to advance the borehole to the top of bedrock (i.e., about 19 feet bgs). The well was constructed of 10 feet of 2-inch-diameter Schedule 40 0.01-inch slot screen (from 9 to 19 feet bgs) and riser.

10GW25

Well 10GW25 is an alluvial monitoring well that was installed the Eichelbergers in July 2000. Air hammer drilling with simultaneous casing advancement was used to advance the borehole to the top of bedrock (i.e., about 26 feet bgs). The well was constructed of 10 feet of 2-inch-diameter Schedule 40 PVC 0.01-inch slot screen (from 16 to 26 feet bgs) and riser.

10GW26

Well 10GW26 is a bedrock monitoring well that was installed the Miller Drilling Company in October 2000. Air hammer drilling with simultaneous casing advancement was used to advance the 12-inch-diameter borehole approximately 5 feet into bedrock (i.e., 28 feet bgs). An 8-inch-diameter steel surface casing was installed to 28 feet bgs and grouted in place. Once the grout around the surface casing set up, air hammer drilling was used to advance an open borehole to a depth of 93 feet bgs.

10GW27

Well 10GW27 is a bedrock monitoring well that was installed the Miller Drilling Company in October 2000. Air hammer drilling with simultaneous casing advancement was used to advance the 12-inch-diameter borehole approximately 5 feet into bedrock (i.e., 30 feet bgs). An 8-inch-diameter steel surface casing was installed to 30 feet bgs and grouted in place. Once the grout around the surface casing set up, air hammer drilling was used to advance an open borehole to a depth of 93 feet bgs.

Appendix B —Well Construction Diagrams

CH2MHILL	PROJECT NUMBER: 152786.FI.FI	WELL NUMBER: 1EW35

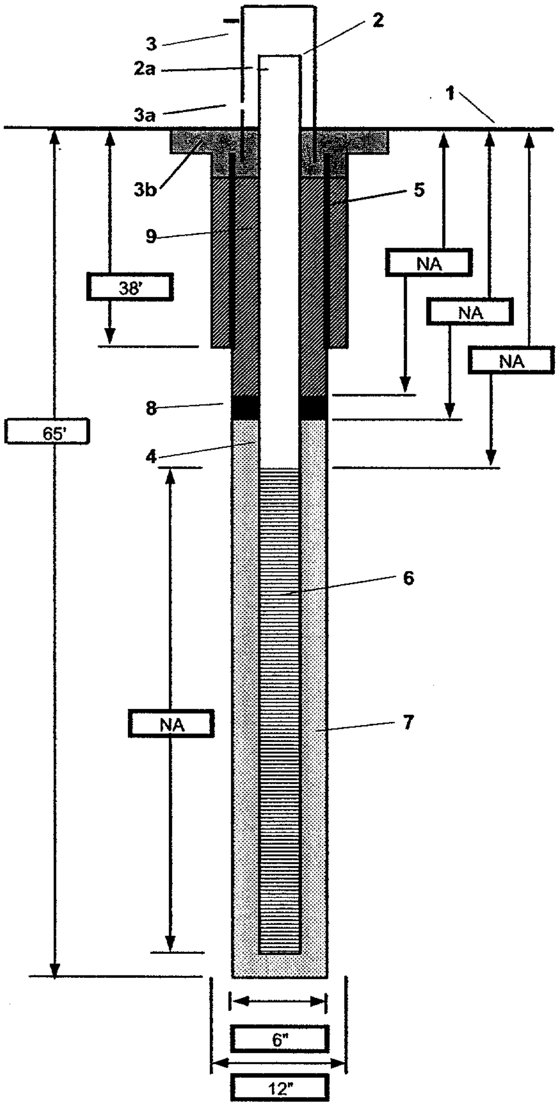
WELL COMPLETION DIAGRAM

PROJECT: LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Eichelbergers

DRILLING METHOD AND EQUIPMENT USED: Air hammer with simultaneous casing advancement to install surface casing, then air hammer

WATER LEVELS : START : 07/26/2000 END: 7/26/2000 LOGGER : F. Calef



1- Ground elevation at well: 674.06

2- Top of casing elevation: 676.43
 a) vent hole?: None

3- Wellhead protection cover type: 10" Steel
 a) weep hole?: None
 b) concrete pad dimensions: None

4- Dia./type of well casing: None

5- Dia./type of surface casing: 10" Steel

6- Type/slot size of screen: None

7- Type screen filter: None
 a) Quantity used:

8- Type of seal: None
 a) Quantity used:

9- Grout
 a) Grout mix used: Portland/Bentonite
 b) Method of placement: Tremie
 c) Vol. of surface casing grout:
 d) Vol. of well casing grout:

Development method: Air Lift

Development time: 1 hr. 21 min.

Estimated development volume: 4,000 gal.

Comments: Surface Casing Set at 38.5' (bgs); Open Borehole to 65' (bgs); Fracture at 58' to 59' (bgs). Well Development Completed on 7/26/00.

CH2MHILL

PROJECT NUMBER: 157286.FI.FI

WELL NUMBER: 10GW23

WELL COMPLETION DIAGRAM

PROJECT :

LOCATION : Allegany ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Alliance Environmental

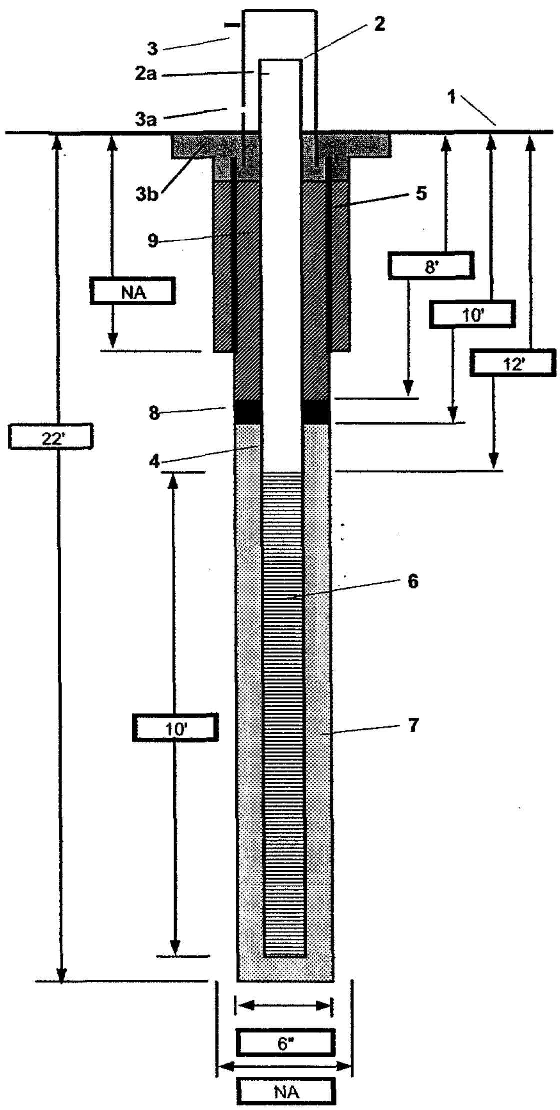
DRILLING METHOD AND EQUIPMENT USED Rotasonic

WATER LEVELS :

START : 07/01/1998

END: 7/1998

LOGGER : R. Doucette/J. Hutton



1- Ground elevation at well	666.44
2- Top of casing elevation	667.48
a) vent hole?	None
3- Wellhead protection cover type	6" Steel
a) weep hole?	None
b) concrete pad dimensions	3' X 3'
4- Dia./type of well casing	2" Schedule 40 PVC Riser
5- Dia./type of surface casing	None
6- Type/slot size of screen	Schedule 40 PVC/0.010"/10' Long
7- Type screen filter	# 1 Silica Sand
a) Quantity used	
8- Type of seal	Bentonite
a) Quantity used	0.5 Bag
9- Grout	
a) Grout mix used	Portland/Bentonite
b) Method of placement	Tremie
c) Vol. of surface casing grout	
d) Vol. of well casing grout	
Development method	
Development time	
Estimated development volume	
Comments	Well Screen Set from 12' to 22' (bgs).

CH2MHILL	PROJECT NUMBER: 157286.FI.FI	WELL NUMBER: 10GW22

WELL COMPLETION DIAGRAM

PROJECT :

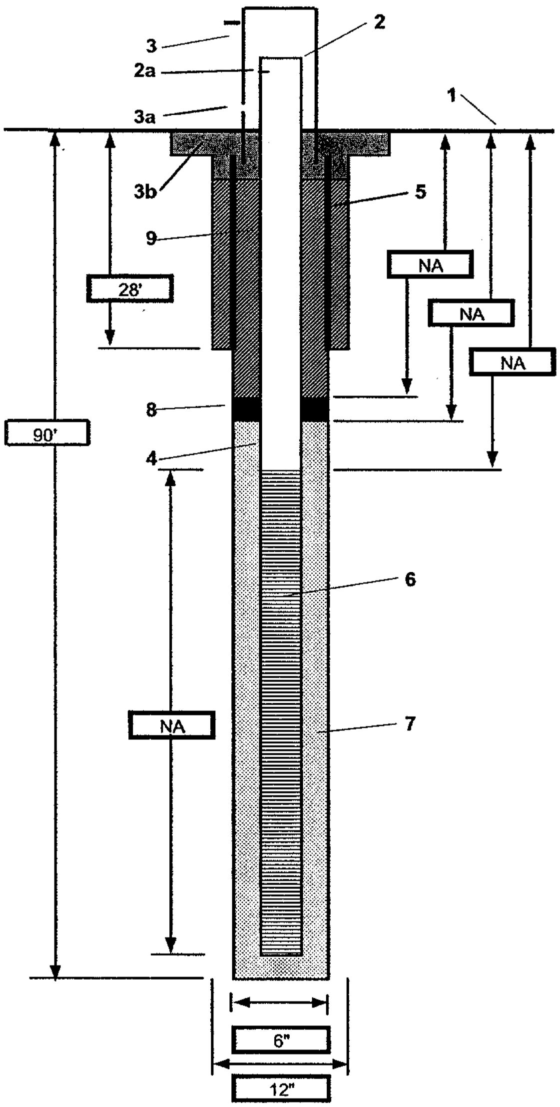
LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Alliance Environmental

DRILLING METHOD AND EQUIPMENT USED Rotasonic, then 6-inch air hammer

WATER LEVELS :

START : 7/1998 END: 7/1998 LOGGER : R. Doucette/J. Hutton



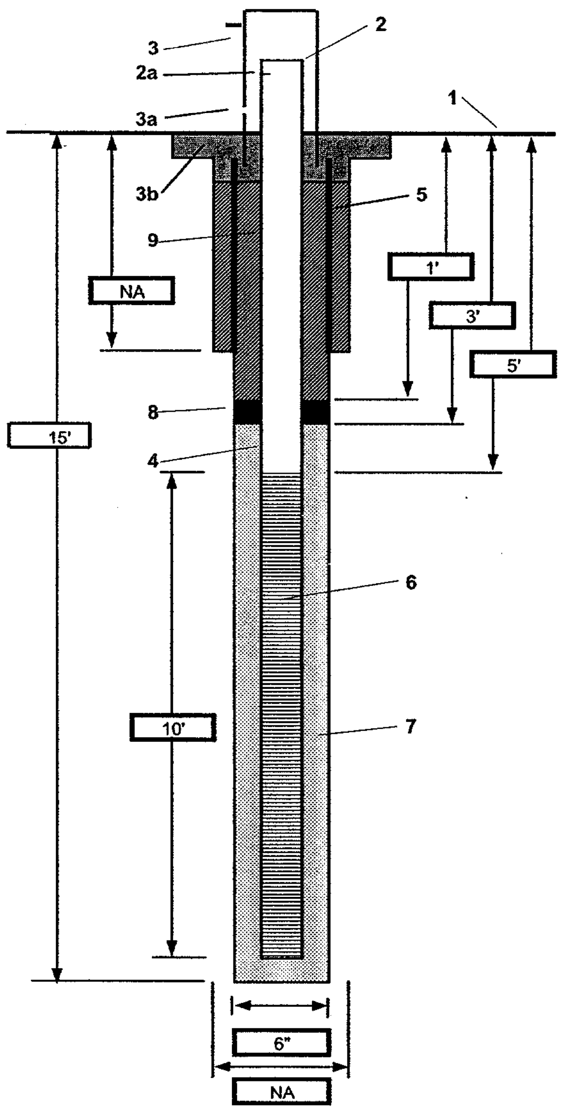
1- Ground elevation at well	664.66
2- Top of casing elevation	665.88
a) vent hole?	None
3- Wellhead protection cover type	8" Steel
a) weep hole?	None
b) concrete pad dimensions	3' X 3'
4- Dia./type of well casing	None
5- Dia./type of surface casing	8" Steel
6- Type/slot size of screen	None - Open Borehole
7- Type screen filter	None
a) Quantity used	
8- Type of seal	None
a) Quantity used	
9- Grout	
a) Grout mix used	Portland/Bentonite
b) Method of placement	Tremie
c) Vol. of surface casing grout	
d) Vol. of well casing grout	
Development method	
Development time	
Estimated development volume	
Comments	Surface Casing Set at 28' (bgs); Open Borehole to 90' (bgs).

CH2MHILL

PROJECT NUMBER: 157286.FI.FI	WELL NUMBER: 10GW21

WELL COMPLETION DIAGRAM

PROJECT :
LOCATION : Allegany ballistics Laboratory, Rocket Center, WV
DRILLING CONTRACTOR : Alliance Environmental
DRILLING METHOD AND EQUIPMENT USED Rotasonic
WATER LEVELS : START : 7/1998 END: 7/1998 LOGGER : R. Doucette/J. Hutton



1- Ground elevation at well: 664.08

2- Top of casing elevation: 665.03
   a) vent hole?

3- Wellhead protection cover type: 6" Steel
   a) weep hole?: None
   b) concrete pad dimensions: 3' X 3'

4- Dia./type of well casing: 2" Schedule 40 PVC Riser

5- Dia./type of surface casing: None

6- Type/slot size of screen: Schedule 40 PVC/0.010"/10' Long

7- Type screen filter: # 1 Silica Sand
   a) Quantity used

8- Type of seal: Bentonite
   a) Quantity used: 0.5 Bag

9- Grout
   a) Grout mix used: Potrland/Bentonite
   b) Method of placement: Tremie
   c) Vol. of surface casing grout
   d) Vol. of well casing grout

Development method

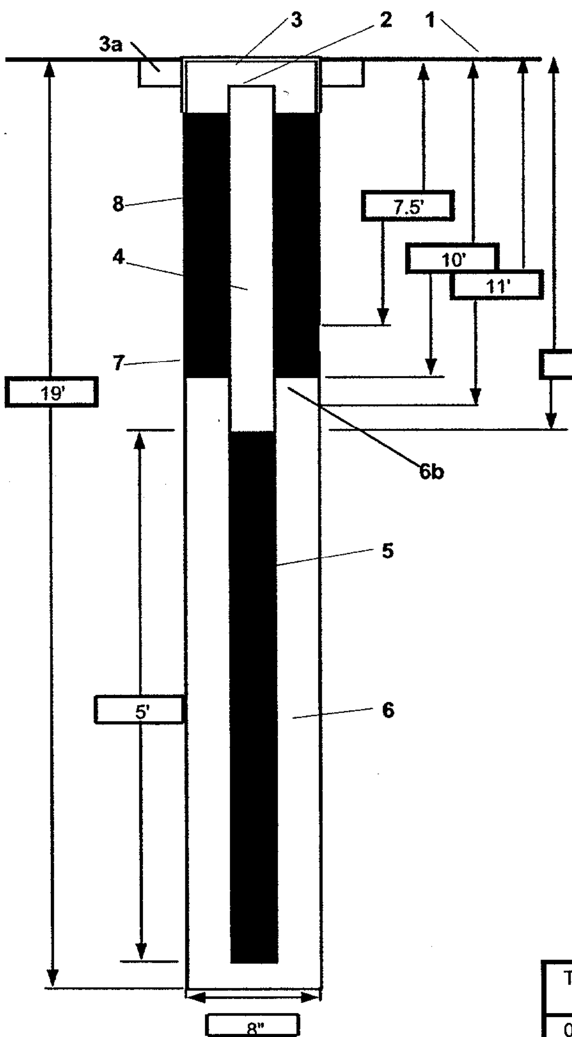
Development time

Estimated development volume

Comments: Well Screen Set from 5' to 15' (bgs).

CH2MHILL	PROJECT NUMBER: 157286.FI.FI	WELL NUMBER: 10EW38
	WELL COMPLETION DIAGRAM	

PROJECT: LOCATION: Allegany Ballistics laboratory, Rocket Center, WV
DRILLING CONTRACTOR: Eichelbergers
DRILLING METHOD AND EQUIPMENT USED: 10" air hammer with simultaneous casing advancement
WATER LEVELS: START: 7/12/2000 END: 7/18/2000 LOGGER: F. Calef



1- Ground elevation at well: 666.02

2- Top of casing elevation: 665.5

3- Wellhead protection cover type: Flushmount Manhole
(a) concrete pad dimensions: 2' X 2'

4- Dia./type of well casing: 6" Schedule 80 PVC Riser

5- Type/slot size of screen: 6-inch Diameter Stainless Steel
0.020" slot/10' Long

6- Type screen filter: # 2 and # 1 Silica Sand
a) Quantity used:
b) Other type:

7- Type of seal: Bentonite
a) Quantity used: 3 Bags

8- Grout
a) Grout mix used: Portland/Bentonite
b) Method of placement: Tremie
c) Vol. of well casing grout:

Development method: Air Lift

Development time: 40 min.

Estimated development volume 55 gal.

Comments Well Screen Set From 13' to 18' (bgs); # 2 Silica Sand from 11' to 19' (bgs); # 1 Silica Sand from 10' to 11' (bgs). Well Development Completed on 7/26/00.

Time	pH	Conductivity	Turbidity	DO	Temperature	Salinity
0818	NA	NA	NA	NA	NA	NA
0827	7.63	0.498	999	NA	15.14	NA
0837	7.32	0.500	280	NA	14.47	NA
847	7.29	0.499	192	NA	15.07	NA
858	7.24	0.495	152	NA	15.39	NA

CH2MHILL

PROJECT NUMBER: 157286.FI.FI

WELL NUMBER: 10EW37

WELL COMPLETION DIAGRAM

PROJECT :

LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Alliance Environmental

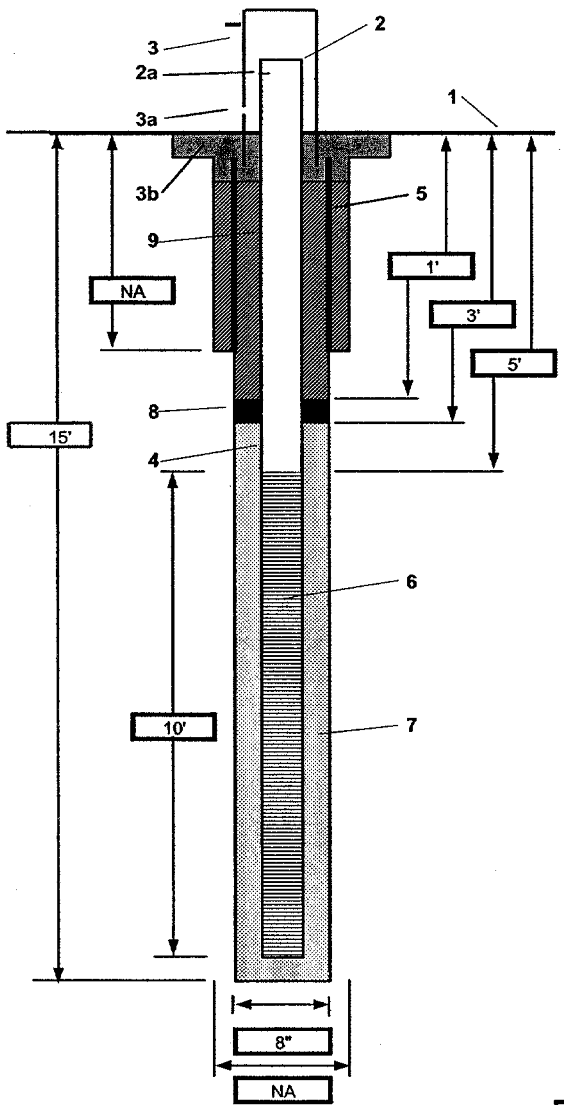
DRILLING METHOD AND EQUIPMENT USEE Rotasonic

WATER LEVELS :

START : 07/1998

END: 7/1998

LOGGER : R. Ducette/J. Hutton



1- Ground elevation at well: 663.83

2- Top of casing elevation: 663.93
a) vent hole?: None

3- Wellhead protection cover type: 4' X 4' X 4' Concrete Manhole Box
a) weep hole?: None
b) concrete pad dimensions: None

4- Dia./type of well casing: 6" Schedule 80 PVC Riser

5- Dia./type of surface casing: None

6- Type/slot size of screen: 6-inch Diameter Stainless Steel/0.020" sl

7- Type screen filter: # 2 Silica Sand
a) Quantity used:

8- Type of seal: Bentonite
a) Quantity used: 2 Bags

9- Grout
a) Grout mix used: Portland/Bentonite
b) Method of placement: Tremie
c) Vol. of surface casing grout:
d) Vol. of well casing grout:

Development method:

Development time:

Estimated development volume:

Comments: Well Screen Set From 5' to 15' (bgs).

Time	pH	Conductivity	Turbidity	DO	Temperature	Salinity

CH2MHILL

PROJECT NUMBER: 157286.FI.FI		WELL NUMBER: 1GW02

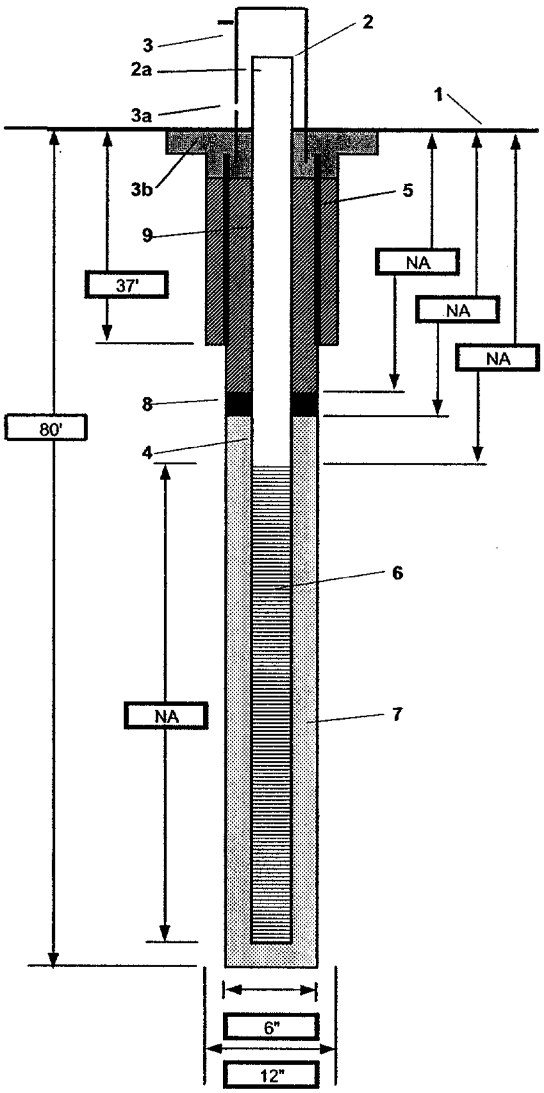
WELL COMPLETION DIAGRAM

PROJECT :   LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Eichelbergers

DRILLING METHOD AND EQUIPMENT USEI Air Hammer

WATER LEVELS :   START : 3/26/2000   END: 4/20/2000   LOGGER : J. Zimmerman



1- Ground elevation at well: 664.53

2- Top of casing elevation: 667.14
   a) vent hole?: None

3- Wellhead protection cover type: 6" Steel
   a) weep hole?: None
   b) concrete pad dimensions: 3' X 3'

4- Dia./type of well casing: None

5- Dia./type of surface casing: 6" Steel

6- Type/slot size of screen: None - Open Borehole

7- Type screen filter: None
   a) Quantity used:

8- Type of seal: None
   a) Quantity used:

9- Grout
   a) Grout mix used: Portland/Bentonite
   b) Method of placement: Tremie
   c) Vol. of surface casing grout:
   d) Vol. of well casing grout:

Development method: Pumping

Development time: 1 hr. 30 min.

Estimated development volume 1,800 gal.

Comments: Surface Casing Set at 37' (bgs); Open Borehole to 80' (bgs). Well Development Completed on 4/20/00.

CH2MHILL

PROJECT NUMBER: 157286.FI.FI

WELL NUMBER: 10GW24

WELL COMPLETION DIAGRAM

PROJECT :

LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Alliance Environmental

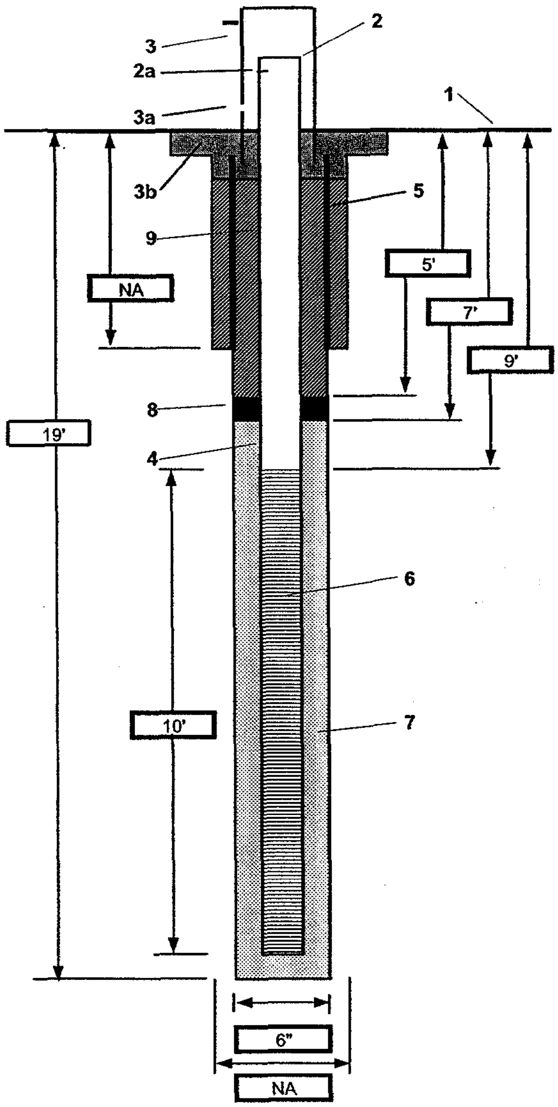
DRILLING METHOD AND EQUIPMENT USEE Rotasonic

WATER LEVELS :

START : 7/1998

END: 7/1998

LOGGER : R. Doucette/J. Hutton



1- Ground elevation at well: 664.08

2- Top of casing elevation: 665.03

a) vent hole?: None

3- Wellhead protection cover type: 6" Steel

a) weep hole?: None

b) concrete pad dimensions: 3' X 3'

4- Dia./type of well casing: 2" Schedule 40 PVC Riser

5- Dia./type of surface casing: None

6- Type/slot size of screen: Schedule 40 PVC/0.010"/10' Long

7- Type screen filter: # 1 Silica Sand

a) Quantity used:

8- Type of seal: Bentonite

a) Quantity used: 0.5 Bag

9- Grout

a) Grout mix used: Portland/Bentonite

b) Method of placement: Tremie

c) Vol. of surface casing grout:

d) Vol. of well casing grout:

Development method:

Development time:

Estimated development volume:

Comments: Well Screen Set from 9' to 19' (bgs).

CH2MHILL

PROJECT NUMBER: 152786.FI.FI

WELL NUMBER: 10GW25

WELL COMPLETION DIAGRAM

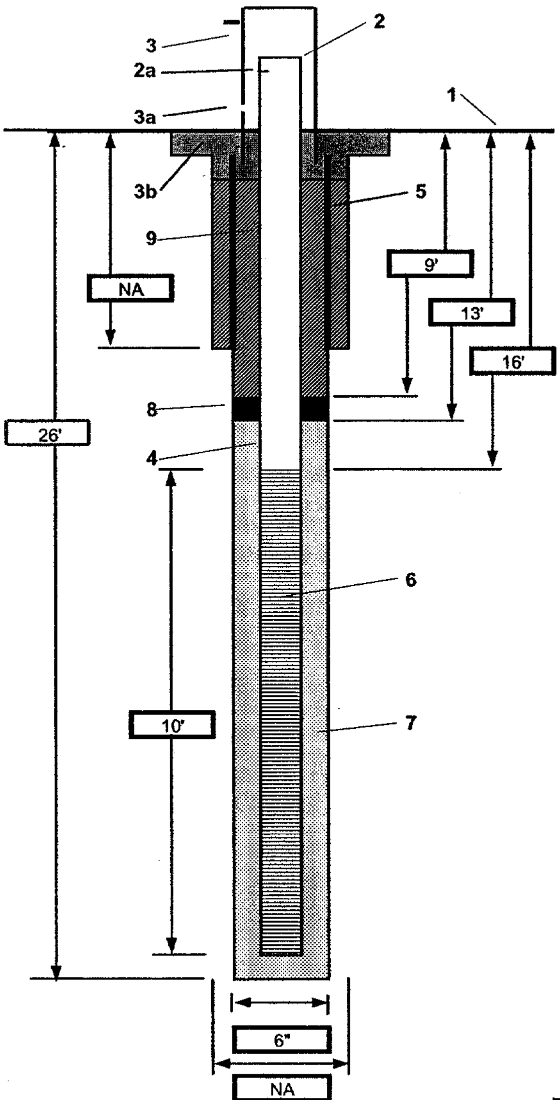
PROJECT:

LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV

DRILLING CONTRACTOR : Eichelbergers

DRILLING METHOD AND EQUIPMENT USED: Air hammer with simultaneous casing advancement

WATER LEVELS : START : 07/11/2000 END: 07/11/2000 LOGGER : F. Calef



1- Ground elevation at well: 666.93

2- Top of casing elevation: 668.78
   a) vent hole?: None

3- Wellhead protection cover type: 6" Steel
   a) weep hole?: None
   b) concrete pad dimensions: 3' X 3'

4- Dia./type of well casing: 2" Schedule 40 PVC Riser

5- Dia./type of surface casing: None

6- Type/slot size of screen: Schedule 40 PVC/0.010"/10' Long

7- Type screen filter: # 2 and # 1 Silica Sand
   a) Quantity used:

8- Type of seal: Bentonite
   a) Quantity used: 2 Bags

9- Grout
   a) Grout mix used: Portland/Bentonite
   b) Method of placement: Tremie
   c) Vol. of surface casing grout:
   d) Vol. of well casing grout:

Development method: Air Lift

Development time: 1 hr. 51 min.

Estimated development volume: 90 gal.

Comments: Well Screen Set from 16' to 26' (bgs); #2 Silica Sand from 14' to 26' (bgs); #1 Silica Sand from 13' to 14' (bgs). Well Development Completed on 7/25/00

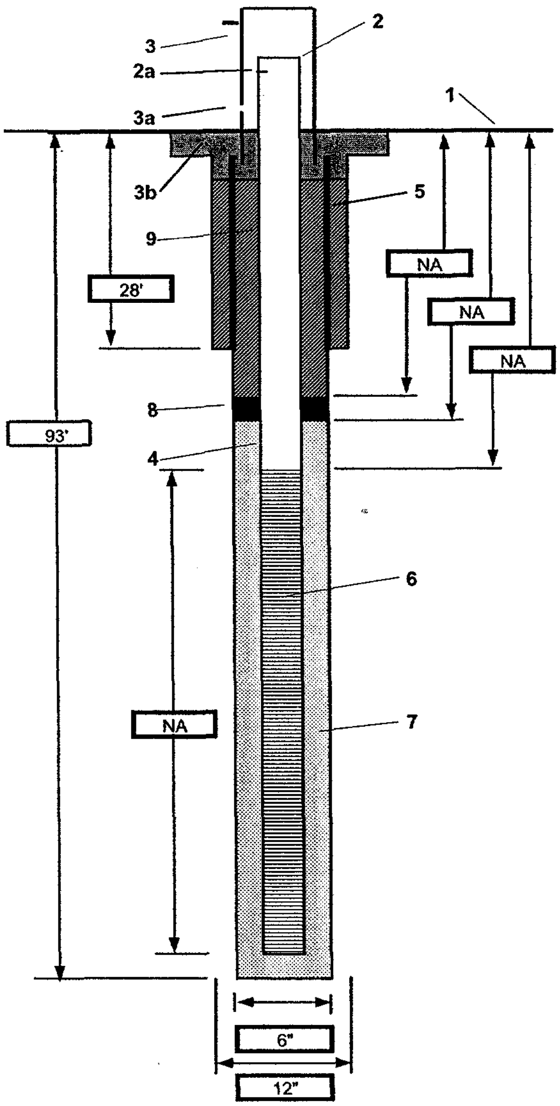
Time	pH	Conductivity	Turbidity	DO	Temperature	Salinity
0804	NA	NA	NA	NA	NA	NA
0805	7.50	0.438	999	NA	15.30	NA
0815	7.01	0.445	999	NA	15.23	NA
0825	7.11	0.446	999	NA	15.14	NA
0835	7.07	0.453	999	NA	15.50	NA
0845	7.09	0.449	466	NA	15.16	NA
0935	6.91	0.413	461	NA	15.80	NA
0945	6.80	0.444	199	NA	15.15	NA
0955	6.89	0.446	94.2	NA	15.46	NA

Well Development: Reading also recorded at 0855.

CH2MHILL	PROJECT NUMBER: 152786.FI.FI	WELL NUMBER: 10GW26

WELL COMPLETION DIAGRAM

PROJECT : LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV
DRILLING CONTRACTOR : Miller Drilling Company, Incorporated
DRILLING METHOD AND EQUIPMENT USEE 12" air hammer with casing advacement, then 6" air hammer
WATER LEVELS : START : 10/08/2000 END: 10/10/2000 LOGGER : J. Zimmerman



1- Ground elevation at well 666.68

2- Top of casing elevation 667.94
 a) vent hole? None

3- Wellhead protection cover type 8" Steel
 a) weep hole? None
 b) concrete pad dimensions 3' X 3'

4- Dia./type of well casing None

5- Dia./type of surface casing 8" Steel

6- Type/slot size of screen None - Open Borehole

7- Type screen filter None
 a) Quantity used

8- Type of seal None
 a) Quantity used

9- Grout
 a) Grout mix used Portland/Bentonite
 b) Method of placement Tremie
 c) Vol. of surface casing grout
 d) Vol. of well casing grout

Development method Air Lift

Development time 1 hr. 50 min.

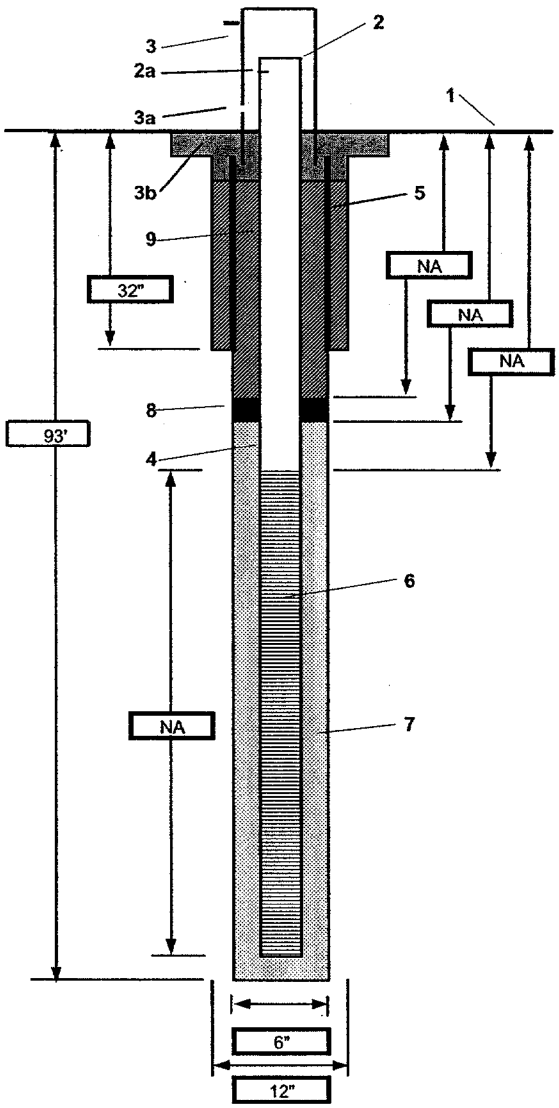
Estimated development volume 600 gal.

Comments Surface Casing Set at 28' (bgs); Open Borehole to 93' (bgs). Well Development Completed on 10/11/00.

CH2MHILL	PROJECT NUMBER: 157286.FI.FI	WELL NUMBER: 10GW27

WELL COMPLETION DIAGRAM

PROJECT :
LOCATION : Allegany Ballistics Laboratory, Rocket Center, WV
DRILLING CONTRACTOR : Miller Drilling Company, Incorporated
DRILLING METHOD AND EQUIPMENT USED 12" air hammer with casing advacement, then 6" air hammer
WATER LEVELS : START : 10/7/2000 END: 10/09/2000 LOGGER : J. Zimmerman



1- Ground elevation at well: 664.48

2- Top of casing elevation: 666.42
   a) vent hole?: None

3- Wellhead protection cover type: 8" Steel
   a) weep hole?: None
   b) concrete pad dimensions: 3' X 3'

4- Dia./type of well casing: None

5- Dia./type of surface casing: None

6- Type/slot size of screen: None

7- Type screen filter: None
   a) Quantity used:

8- Type of seal: None
   a) Quantity used:

9- Grout
   a) Grout mix used: Portland/Bentonite
   b) Method of placement: Tremie
   c) Vol. of surface casing grout:
   d) Vol. of well casing grout:

Development method: Air Lift

Development time: 2 hrs. 5 min.

Estimated development volume 600 gal.

Comments Surface Casing Set at 32' (bgs); Open Borehole to 93' (bgs). Well Development Completed on 10/10/00.

Appendix C —Yield Test of Well 1EW35 at Allegany Ballistics Laboratory, Site 1

MEMORANDUM **CH2MHILL**

Yield Test of Well 1EW35 at Allegany Ballistics Laboratory, Site 1

TO: Brett Doerr/WDC

FROM: John Glass/WDC

DATE: August 22, 2000

Background and Purpose

A groundwater remediation system consisting of 27 alluvial extraction wells and 7 bedrock extraction wells has been in operation at Allegany Ballistics Laboratory (ABL) Site 1 since September 1998. Its primary remediation objective is to provide hydraulic containment of groundwater contaminated with volatile organic compounds (VOCs), primarily trichloroethene (TCE), and prevent its discharge to the North Branch Potomac River. Figure 1 shows the locations of the extraction and monitoring wells at Site 1 and their geographic relationship to the river.

The performance of the groundwater remediation system is evaluated in several ways. The most basic form of performance monitoring is to compare the water levels in 10 monitoring wells located near the river bank with the water surface elevation in the river. If the groundwater levels are all lower than the river level, the system is assumed to be achieving its hydraulic containment goal. The 10 primary performance monitoring wells are (from west to east) 1GW39, 1GW34, 1GW35, 1GW37, and 1GW38 in the Alluvial Aquifer, and 1GW12, 1GW9, 1GW36, 1GW4, and 1GW14 in the Bedrock Aquifer.

After nearly two years of performance monitoring, it is apparent that hydraulic containment is generally successful across Site 1 except at the westernmost end. In the 1999 Performance Monitoring Report was noted that the groundwater levels in bedrock monitoring well 1GW12 are generally slightly higher than the river level, as measured due north of Site 1. During periods when the river level is stable, the water in Well 1GW12 is generally 0.2 to 0.4 feet higher than the river. When the river level fluctuates, groundwater in Well 1GW12 may be up to 1 foot higher than the river for short periods. At these times, the water levels in the adjacent alluvial monitoring well, 1GW39, may also be higher than the river, although that is not normally the case.

Because of the difficulties experienced in maintaining water levels below the river level at Monitoring Well 1GW12, it was decided that an additional bedrock extraction well should be installed near it. On July 25 and 26, 2000, the new extraction well, 1EW35, was installed approximately eight feet north of Alluvial Extraction Well 1EW26 (see Figure 1). The driller encountered bedrock at a depth of 38 feet below ground surface and installed a 10-inch surface casing to 38.5 feet below ground surface. At 40 feet, a water-yielding fracture was encountered in the black shale bedrock. The well was installed as an open 6-inch borehole to a total depth of 65 feet. The open portion of the bore-hole encountered a major water-yielding fracture in the depth interval between 58 and 59 feet.

To test the potential of the new bedrock well to help in controlling water levels at the west end of Site 1, a five-hour yield test was run on August 3, 2000. This memorandum describes the procedures used in the yield test of Well 1EW35, presents the test results, and provides some analysis of the test data.

Yield Test Procedures

Pumping

An electric pump with a maximum capacity of 66 gallons per minute (gpm) was temporarily installed in Well 1EW35 for the yield test. Because the groundwater to be pumped was potentially contaminated, the water withdrawn during the test was contained in a portable 21,000 gallon tank for subsequent transfer to the groundwater treatment plant.

Pumping from well 1EW35 was started at 14:55 on August 3, 2000. The initial pumping rate was 50 gpm. After 130 minutes, the water level in the pumping well appeared to have stabilized at a drawdown of approximately 0.45 feet. The pumping rate was then increased to 60 gpm, which was maintained for 148 minutes. At that time, the water level in Well 1EW 35 was observed to be rising, and it was thought that the rise might be caused by rain earlier in the day. The pumping rate was then increased to 66 gpm for an additional 32 minutes. The yield test ended at 22:05, after a total of 5 hours and 10 minutes of pumping.

Water-Level Monitoring

Since the purpose of the yield test was to find both the capacity of the new well and its potential to lower groundwater levels at the west end of Site 1, water levels were monitored in several nearby wells in addition to the well being tested. Temporary pressure transducers attached to digital data loggers were installed in wells 1EW35 and 1GW2 prior to the start of the yield test. In addition, several nearby monitoring wells have permanent pressure transducers that are continuously monitored by the programmable logic controller (PLC) at the groundwater treatment plant. The closest of these to the tested well are monitoring wells 1GW12, 1GW39, 1GW9, 1GW34, and extraction wells 1EW25, 1EW26, 1EW27, and 1EW28. The pumps in those four extraction wells were turned off the day before the test so that the wells could be used to monitor the yield test of Well 1EW35.

Before the yield test was started, the water levels were measured by hand in all of the monitoring wells to be observed so that the transducer readings could be accurately interpreted as absolute water levels. The river level was also measured manually at the upstream staff gauge (see Figure 1) so that the river-level record collected automatically by the PLC could be accurately related to the observed groundwater levels. Water levels in the newly installed well, 1EW35, could not be related to mean sea level (MSL) because that well has not yet been surveyed.

The three extraction wells at Site 10, about 2,000 feet south of Site 1, were also turned off and used to monitor water levels during the yield test. However, those Site 10 well showed no responses that could be related to the pumping of Well 1EW35. Therefore, they will not be discussed further.

Other Monitored Parameters

In addition to the water levels mentioned above, the temperature of the groundwater was monitored in Well 1EW35 before, during, and after the yield test. Temperature was to be used as a natural tracer in an attempt to evaluate the degree of interconnection between the tested well and the river. The natural groundwater temperature observed prior to the test at Well 1EW35 was approximately 13.8 degrees C., while the water temperature near the bottom of the river was approximately 22 degrees C.

Well 1EW35 was also sampled at the beginning and at the end of the yield test. The samples were analyzed for VOCs, dissolved iron, manganese, and total suspended solids (TSS).

Test Results

River Level Fluctuations

A continuous river-level record was recorded by the ABL pressure transducer located in the river near the downstream staff gauge on the eastern end of Site 1. An additional record of river-level fluctuations was also obtained from the U. S. Geological Survey's Pinto Gauging Station, which is located approximately 500 feet upstream of the west end of Site 1. Figure 2 shows these river-level records for a period from about 19 hours before the yield test to about 18 hours after the test. Note that the river levels were fairly constant before the test but that they increased by approximately 0.5 feet during the second half of the test. The effects of this increase in river levels were observed in most of the wells monitored during the test, and somewhat complicated the evaluation of the test results.

In addition to the water levels at the two automatically recorded gauging stations, Figure 2 also shows the estimated water level record at the upstream staff gauge. This staff gauge is located on the south side of the river near the area of interest. Its water-level record, as shown in Figure 2, was constructed by adding 0.50 feet to the record obtained from the ABL river gauge at the east end of Site 1. The correction of 0.50 feet was obtained by comparing the manual measurement of water level made at the upstream staff gauge with the automatically collected reading from the ABL river transducer.

Observed Groundwater and Temperature Fluctuations

Figure 3 shows the record of depth-to-water and water temperature in Well 1EW35 measured before, during, and after the yield test. The depth to water record is presented as an initial indication of the drawdown observed in the pumped well during the yield test and of the effects of river fluctuation on the well. The record shows an initial drawdown of approximately 0.4 feet coincident with the start of pumping at 50 gpm. (The short spike of drawdown several minutes before the start of the yield test was caused by a momentary test of pump operation.) Additional drawdown is observed in the middle of the yield test when the pumping rate was increased to 60 gpm. Shortly after that, however, the drawdown began to decrease, indicating rising groundwater caused by the increase in river level. It is apparent that this new well has a fairly direct hydraulic connection to the river. The connection is probably the result of bedrock fracturing.

Figure 3 also shows the record of water temperatures in Well 1EW35. Prior to the yield test, the groundwater temperature was approximately 13.75 C. The temperature remained constant for approximately the first two hours of the yield test. Then it began to rise almost linearly and continued to rise until the pump was turned off. This suggests that pumping caused warmer water from the river to start entering the well after about two hours of pumping. The increase in water temperature appears to start just before the river began to rise at the ABL gauge. However, Figure 2 appears to show the river level at the USGS gauging station upstream of Site 1 rising at about the same time at the temperature in Well 1EW35. It is possible that this is coincidental. The two-hour lag in the start of the temperature increase may indicate the travel time of water from the river to the well.

Observed Water Levels in Monitoring Wells

Figure 4 shows the observed water levels in the bedrock monitoring wells during and after the yield test. The figure also shows the estimated river level at the upstream staff gauge for reference.

The response of Well 1GW12 is of special interest because that is the well that has historically had water levels higher than the river. At the start of the yield test, the water level in 1GW12 was about 0.58 feet higher than the river. That was a somewhat greater difference than has typically been observed during routine monthly water-level monitoring. During the first 180 minutes of the test, before the river began to rise, Well 1GW12 responded to pumping with a drawdown of approximately 0.37 feet. It is not clear from Figure 4 whether the water level in 1GW12 would have eventually been drawn down below the river level if the river had remained stable. When the river began to rise, the level in 1GW12 rose also, and therefore remained higher than the river throughout the period shown.

The water level in Well 1GW2 behaved in much the same way as 1GW12, but with variations of smaller magnitude. Well 1GW2 is a shallow bedrock well that has an effective open interval from 29 to 40 feet below ground surface. Well 1GW12 is open to the deeper bedrock from 70 to 80 feet. As Figure 4 shows, the drawdown induced in 1GW2 by pumping 1EW35 was small. But it was enough to depress the water level to an elevation lower than the river while the river remained stable.

Figure 5 shows the response of water levels in the monitored alluvial wells during and after the yield test. The well of greatest interest is 1GW39, which is located adjacent to the bedrock wells 1GW2 and 1GW12. At the start of the yield test, water in 1GW39 was at the same level as the river. During the first three hours of pumping at 1EW35 a drawdown of about 0.1 foot was observed. Under stable river conditions, that drawdown would probably have continued to increase. Drawdown normally develops more slowly in an unconfined alluvium because of its greater storage capacity. Although the drawdown in 1GW39 stopped when the river began to rise, the water level in the well remained below the river level until pumping at 1EW35 was terminated.

It may be noted that the water levels in Alluvial Extraction Well 1EW27 were abut 0.3 feet higher than the river level throughout the period illustrated in Figure 5. That extraction well had been turned off so that it could be used to monitor the test. Under normal pumping conditions, it's water level would be lower than the river.

Drawdown Estimates Corrected for River Fluctuations

One purpose of the yield test at the new well, 1EW35, was to evaluate its hydraulic effect on water levels in the surrounding portions of the bedrock and alluvial aquifers. Direct quantitative observation of the aquifer response was made more difficult by the untimely fluctuations in river level that occurred during the test. However, by observing the relationships between river and groundwater fluctuations before and after the yield test, the effects of river variations can be at least partially removed from the observation well records. This procedure gives a more accurate estimate of the hydraulic response of the groundwater system to pumping at Well 1EW35 than do the uncorrected observations discussed in the preceding section.

As an illustration of the correction, Figure 6 shows the estimated drawdown in the tested well, 1EW35, with the effects of river fluctuations removed. The time-drawdown curve in Figure 6 was prepared from the raw depth-to-water data illustrated in Figure 3. Drawdown was calculated by subtracting the depth-to-water at the start of the test from the subsequent depth-to-water measurements. The resulting raw drawdown value was then modified by subtracting the change in river levels over the same time period after multiplying the river change by an efficiency factor. The efficiency factor is a measure of the response of water levels in the well to changes in river level. It was determined by comparing the magnitude of water-level fluctuations in the well and the river observed at a time when the well was not being pumped. In this instance, the roughly sinusoidal fluctuations observed several hours after the end of the yield test (see figures 2 and 3) were used. Surprisingly, an efficiency factor of 130 percent was needed to remove the sinusoidal river fluctuations from the raw depth-to-water record from Well 1EW35. This means that fluctuations in the well were actually greater than in the river at the upstream staff gauge. How is that possible? One possibility is that groundwater in the area of Well 1EW35 may be connected by bedrock fractures to an upstream portion of the river above the rapids, where river-level fluctuations may have been higher than those recorded by the ABL river transducer. Another possibility is that the river-level fluctuations occurring at the upstream staff gauge were greater than those recorded at the ABL transducer.

Figure 6 shows that even with a 130-percent correction for river-level fluctuations, the drawdown declined after the pumping rate in Well 1EW35 was increased to 60 gpm. This apparently means that a response efficiency of 130 percent was not enough to completely remove large river-level fluctuations. Hence, the corrected drawdown record shown in Figure 6 is only an approximate estimate of the well's hydraulic response to pumping.

Figure 7 shows the water-level records in the other wells monitored during the yield test, with corrections for river-level fluctuations. The response efficiencies used in the corrections were determined independently for each well, and ranged from 31 percent at 1GW34 to 135 percent at 1GW9. The reason for making these corrections was to get a better estimate of aquifer response to pumping at Well 1EW35 than the raw drawdown data would provide. Even with correction for river-level variations, little or no response can be observed in some of the monitored wells. For the wells where a definite hydraulic response was apparent, Table 1 lists the response magnitudes. The response at the critical well, 1GW12, suggests that pumping 60 gpm at Well 1EW35 could potentially provide the needed reduction in water levels under typical conditions with stable river levels. However, the pumping rate is relatively high for such a limited hydraulic response, and the behavior experienced during the test shows that depressed water levels can not be maintained at Well 1GW12 when the river levels fluctuate.

Table 1
Yield Test at Well 1EW35, August 3, 2000
Estimated Drawdown Responses at Monitoring Wells
(Corrected for River-Level Fluctuations)

Well	Terminal Drawdown at 50 gpm (in Feet)	Terminal Drawdown at 60 gpm (in Feet)
1GW2	0.08	0.06
1GW12	0.30	0.48
1EW25	0.12	0.22
1EW26	0.25	0.39
1EW27	0.07	0.08
1EW28	0	0.05

Water Quality Sampling Results

Samples were taken from Well 1EW35 for water quality analysis at the beginning and at the end of the five-hour yield test. The beginning sample was taken after the well had been pumped at 50 gpm for eight minutes. The ending sample was taken two minutes before the pump was shut off at the end of the test. The samples were analyzed for VOCs, iron, manganese, and total suspended solids (TSS). The VOC scans were done with EPA Method 624. The only two volatile organic constituents detected were TCE and trichlorofluoromethane (TCFM). The detection results are listed in Table 2.

Table 2
Yield Test of Well 1EW35, August 3, 2000
Summary of Water Quality Sampling Results

Parameter	Beginning Sample	Ending Sample
Trichloroethene	14 µg/L	10 µg/L
Trichlorofluoromethane	4.3 µg/L	ND
Iron	34,200 µg/L	8,290 µg/L
Manganese	2,190 µg/L	667 µg/L
Total Suspended Solids	133 mg/L	94.8 mg/L

Note: ND = below method detection limit

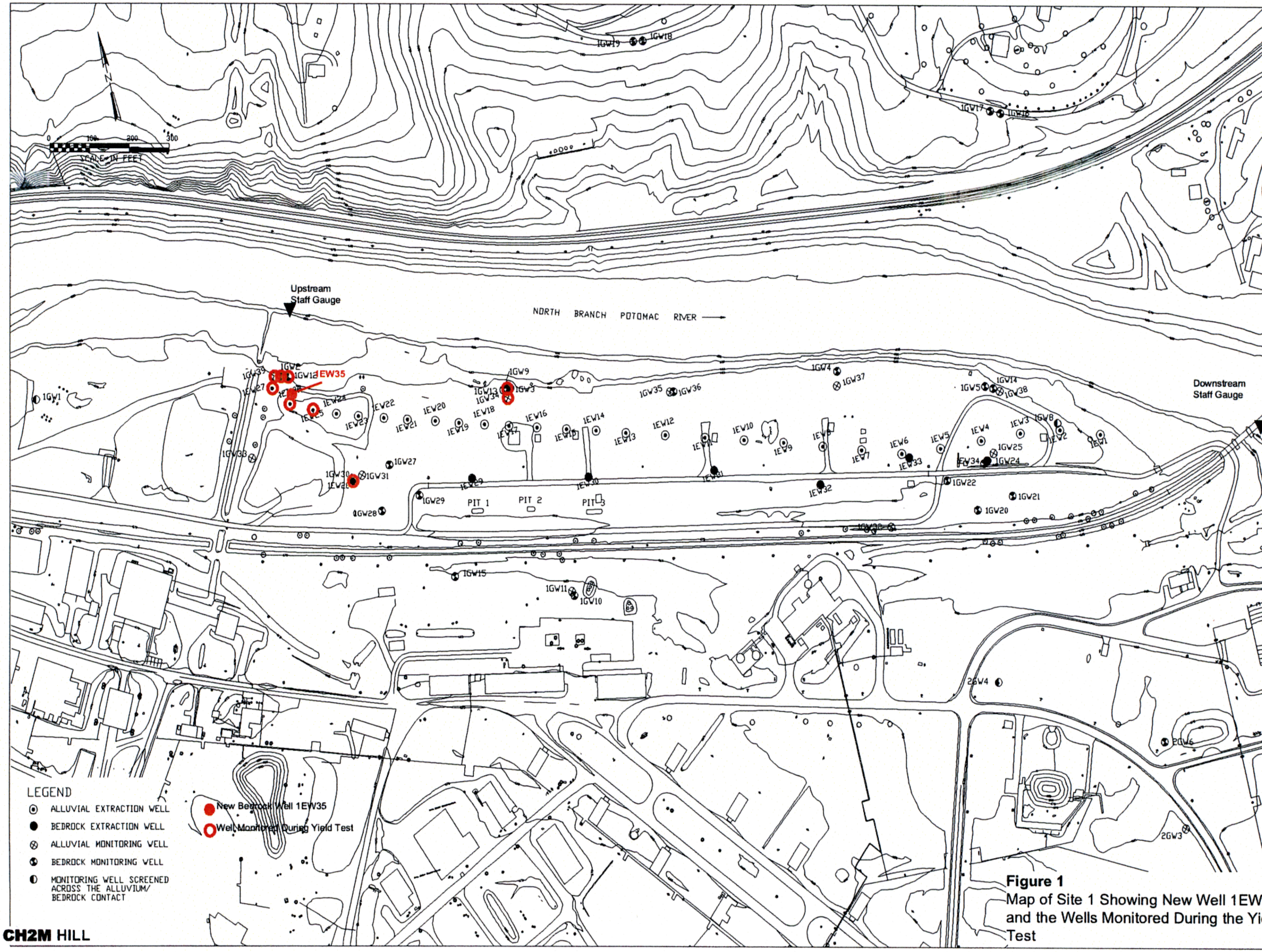


Figure 1
Map of Site 1 Showing New Well 1EW35 and the Wells Monitored During the Yield Test

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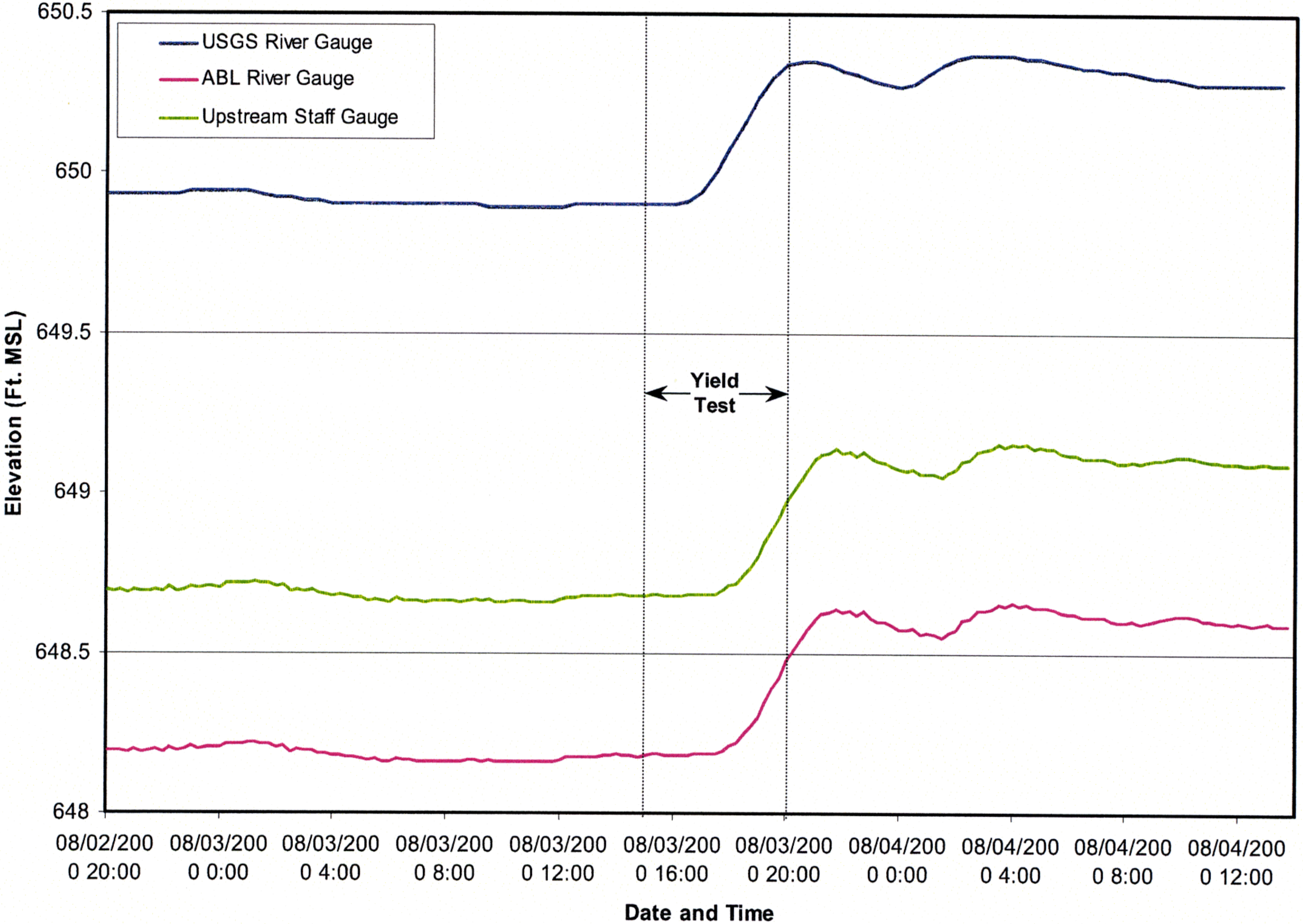

Figure 2
Record of River-Level Fluctuations Before, During, and After the Yield Test at Well 1EW35

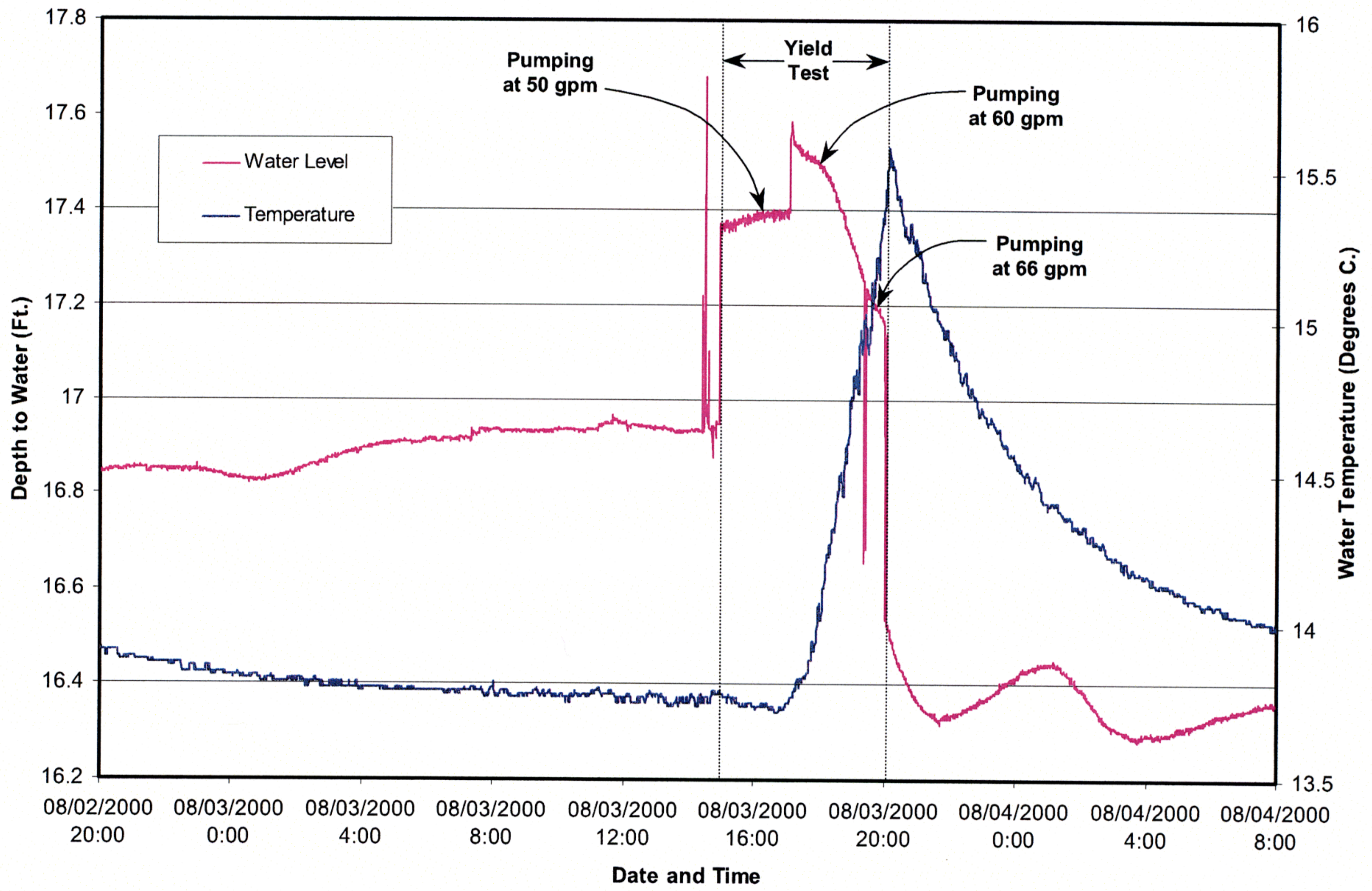

Figure 3
Water-Level and Temperature Records in Well 1EW35 Before, During, and After the Yield Test
(Water Levels not Corrected for River Fluctuations)

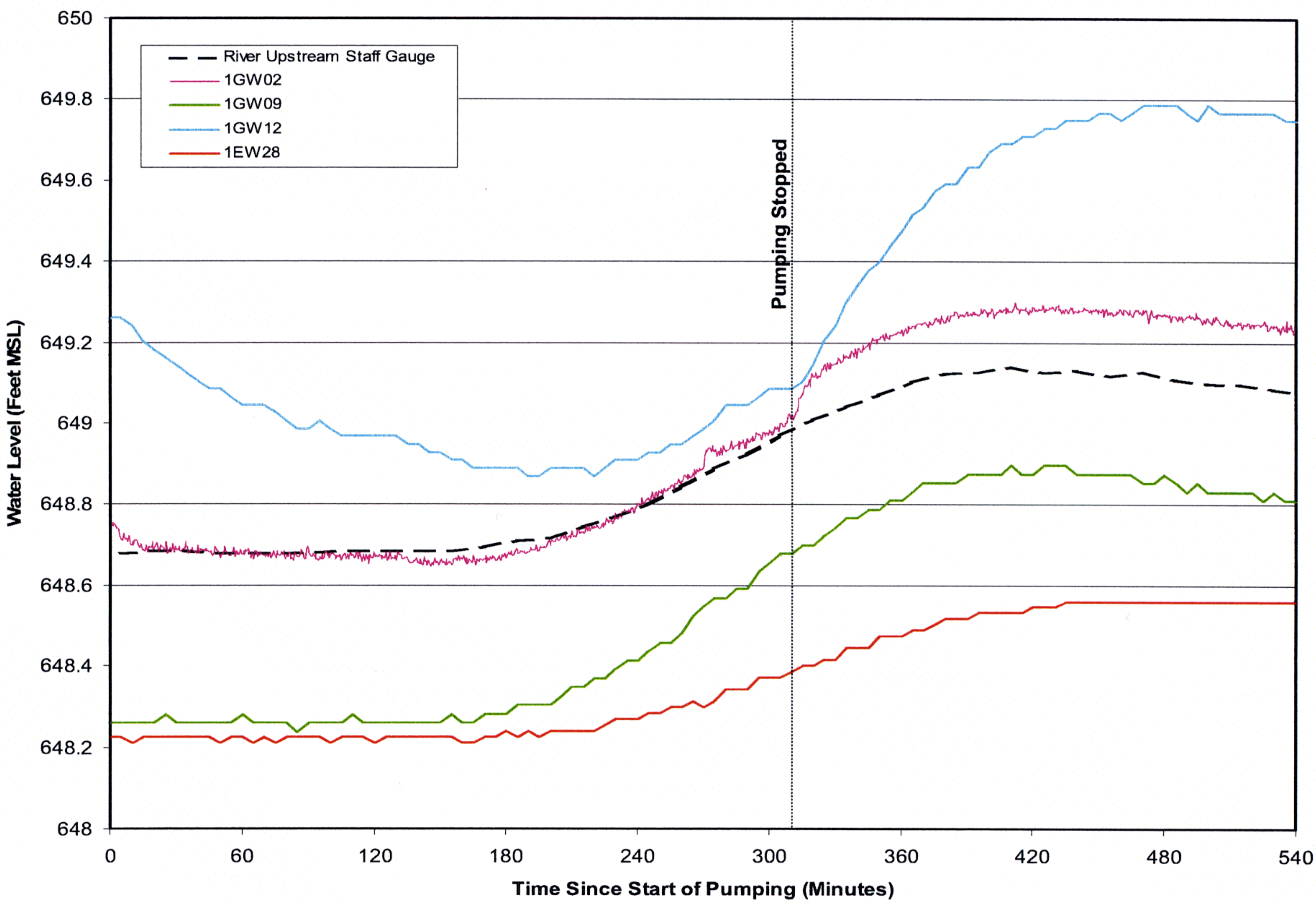

Figure 4
Measured Water Levels in Bedrock Monitoring Wells and the River

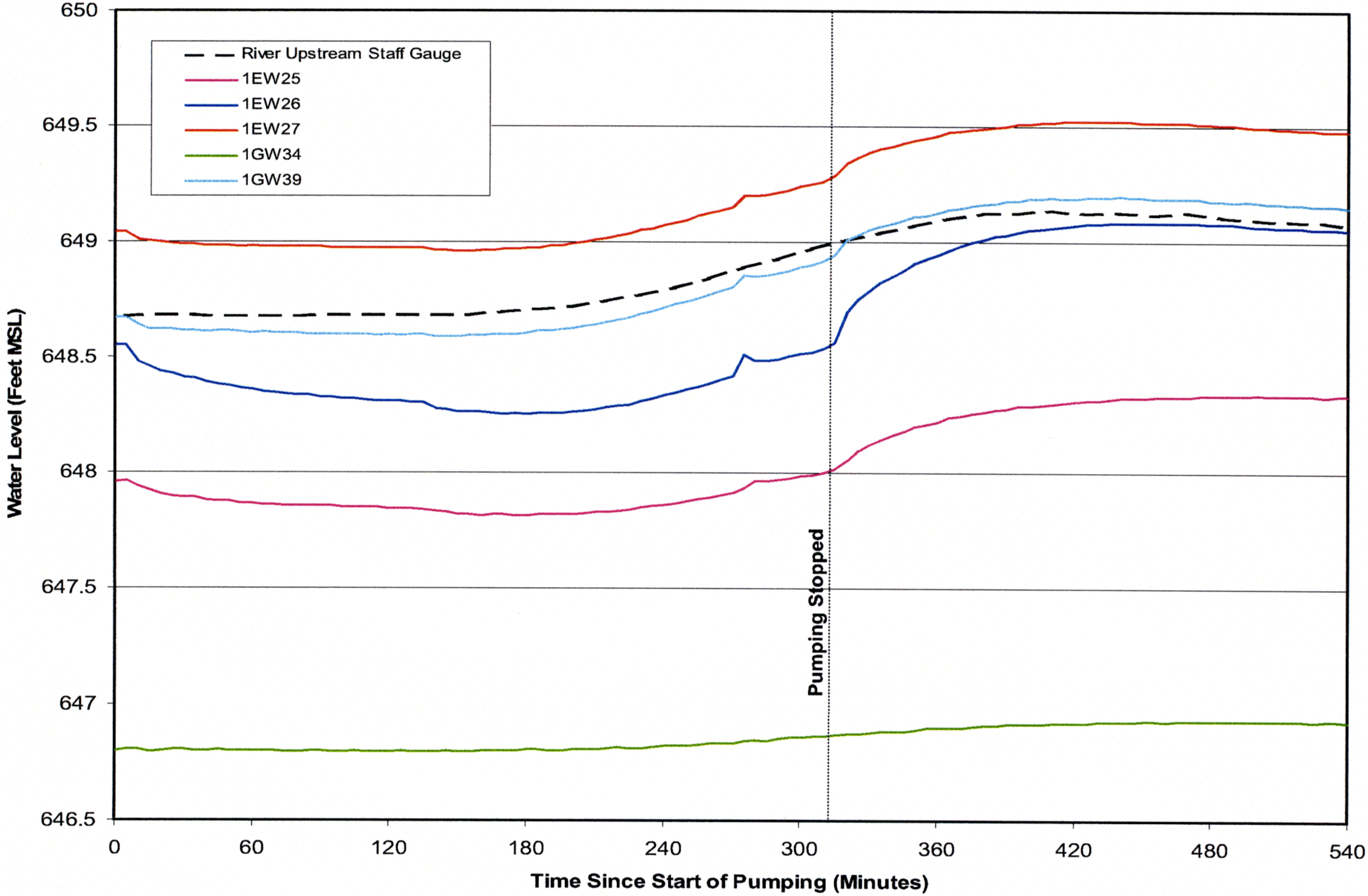

Figure 5
Measured Water Levels in Alluvial Monitoring Wells and the River

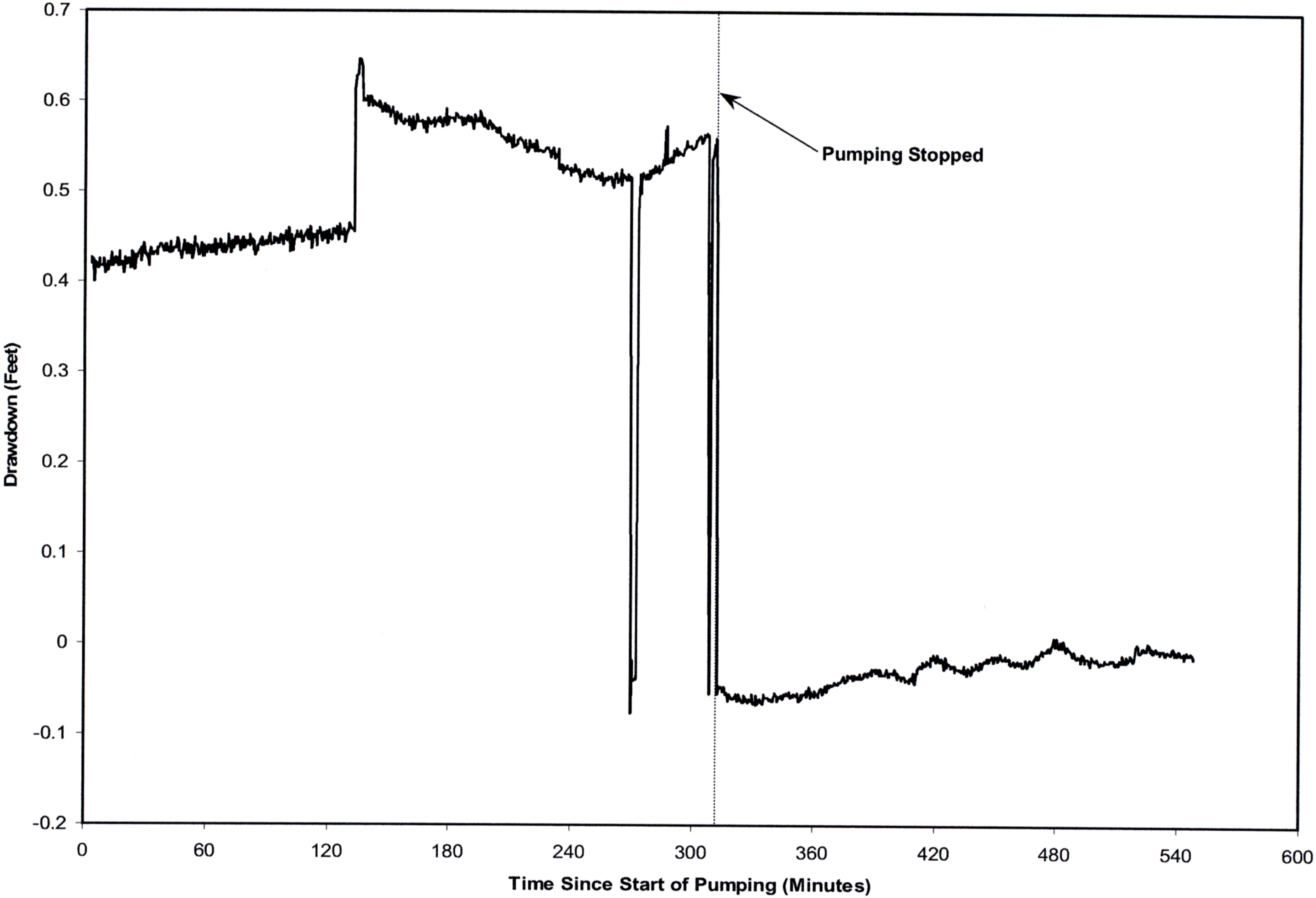

Figure 6
Drawdown and Recovery Record in Well 1EW35, Corrected for River Level Fluctuations

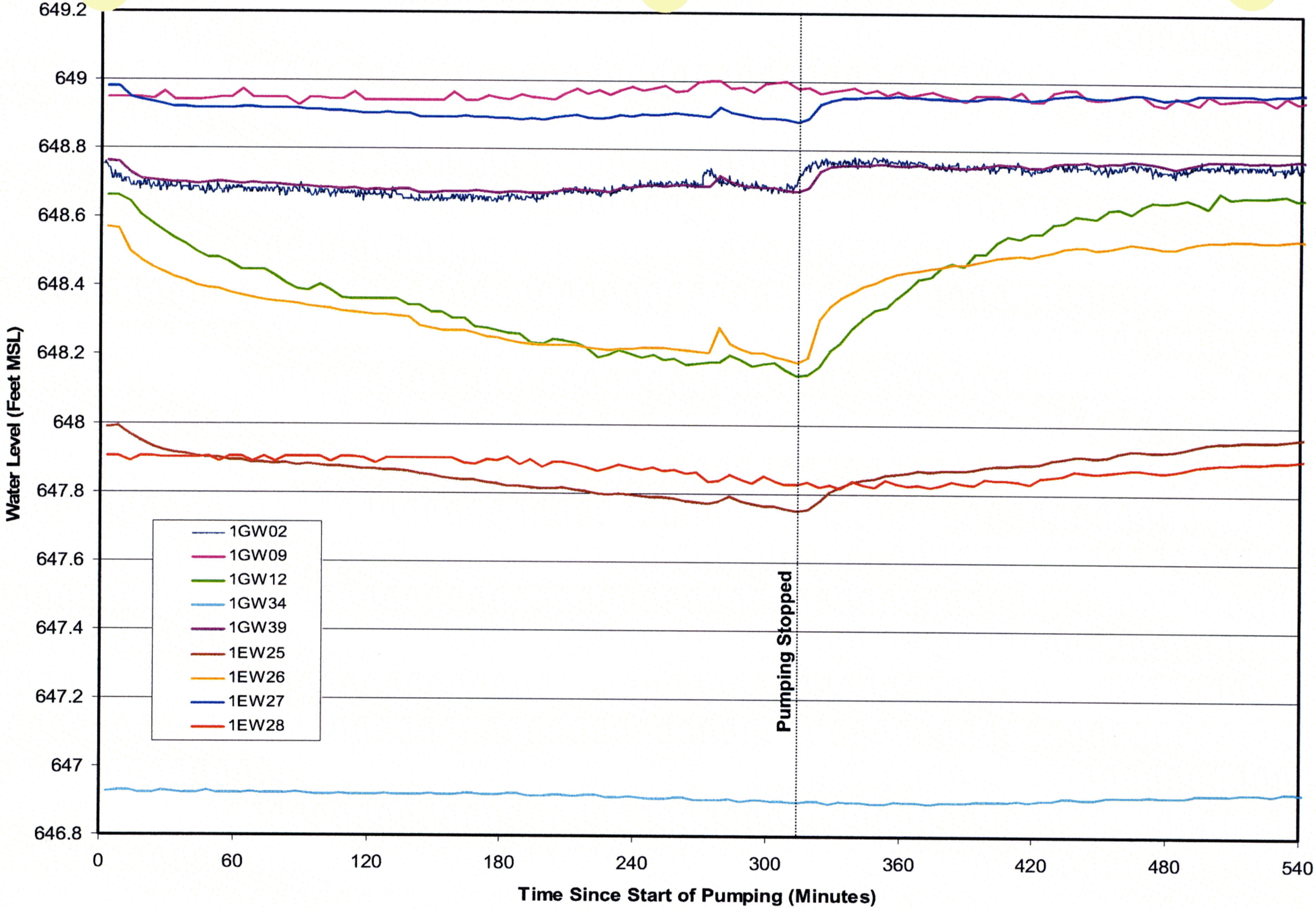

Figure 7
Water-Level Records from the Monitoring Wells, Corrected for River Fluctuations

Appendix D —Water-Level Records from Data Loggers

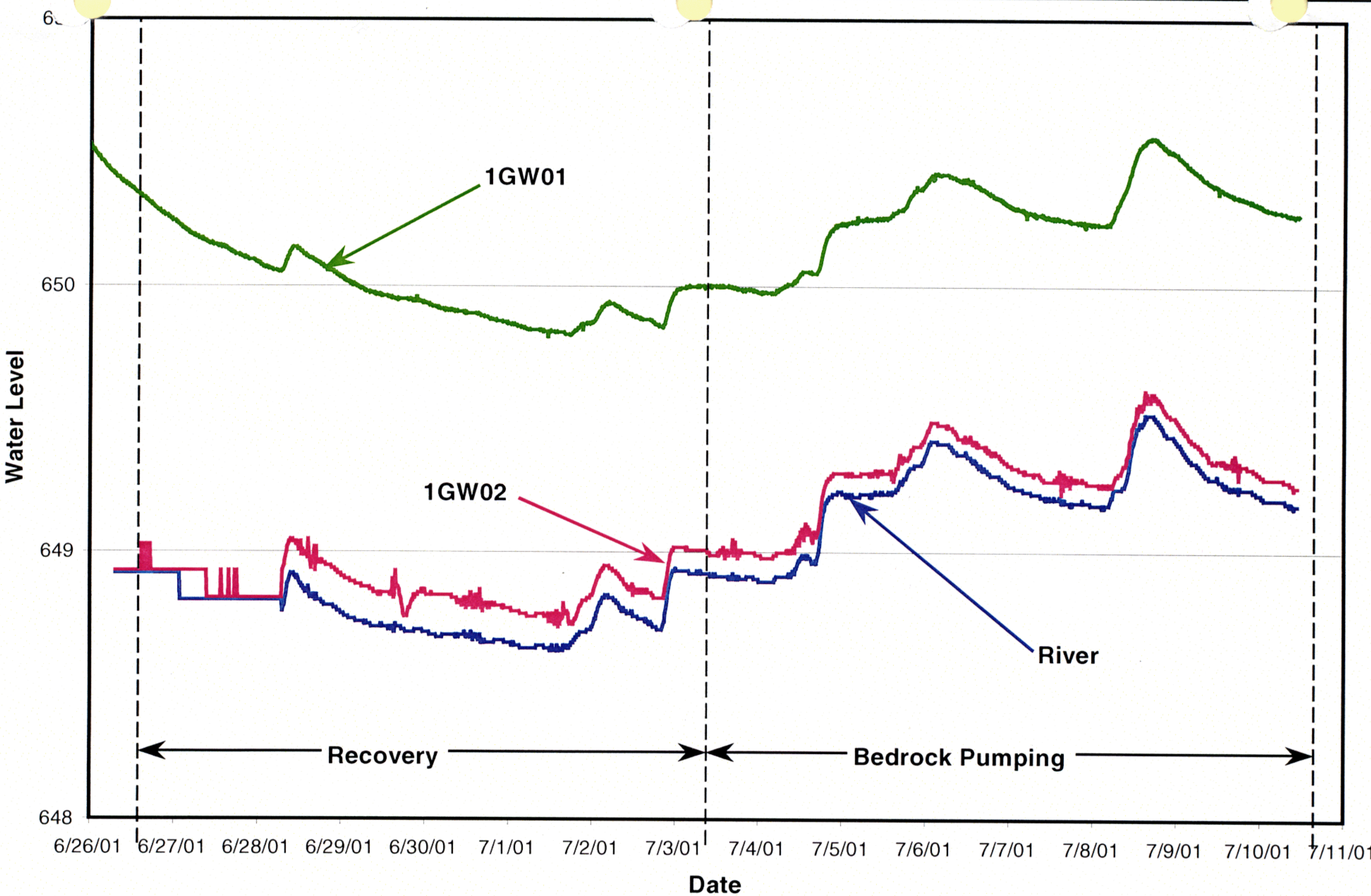

Figure D-1
Water-Level Records from Data Loggers in Wells 1GW01, 1GW02, and the Upstream River Gauge
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

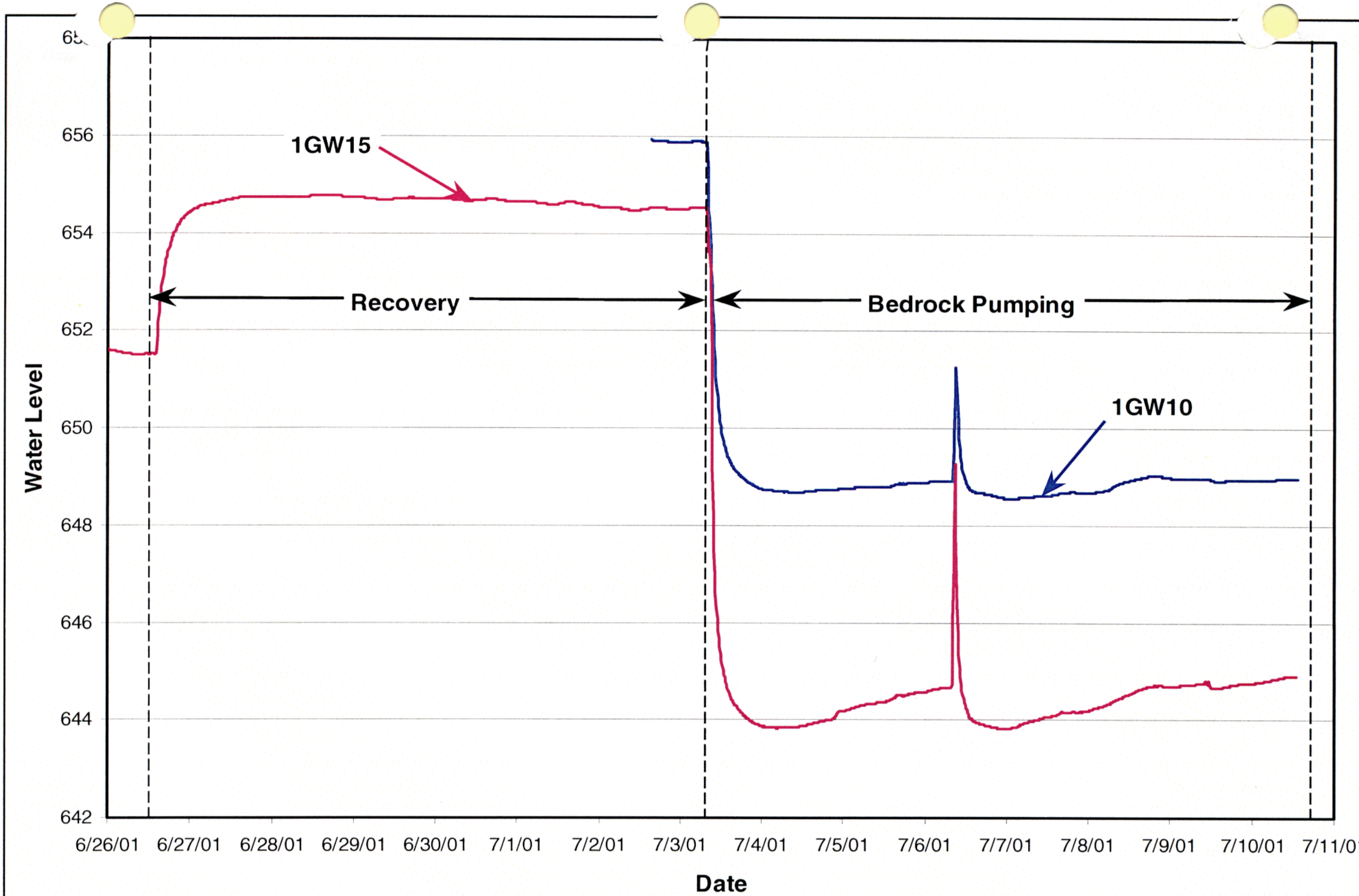

Figure D-2
Water-Level Records from Data Loggers in Wells 1GW10 and 1GW15
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

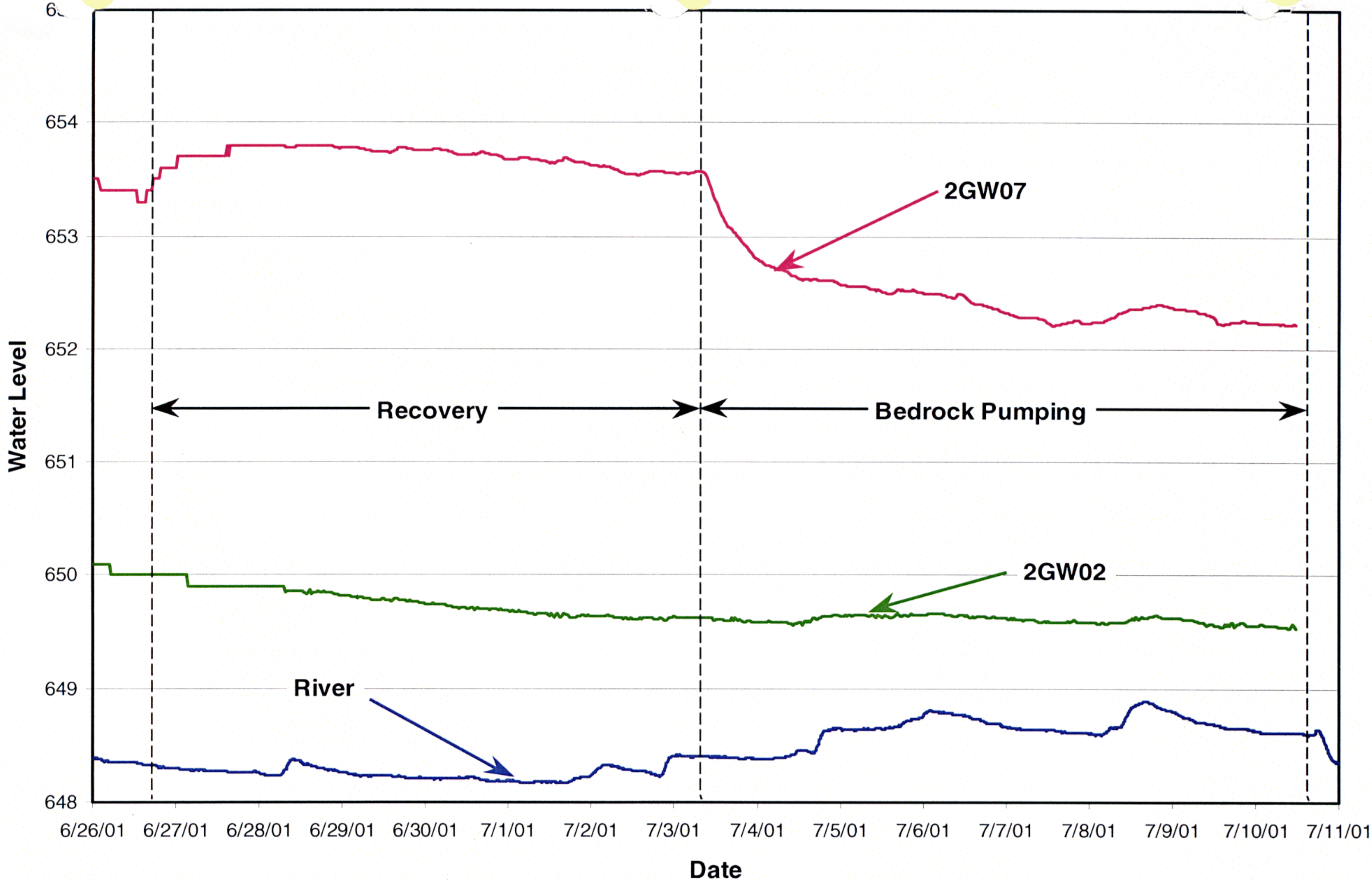

Figure D-3
Water-Level Records from Data Loggers in Wells 2GW02, 2GW07, and the Downstream River Gauge
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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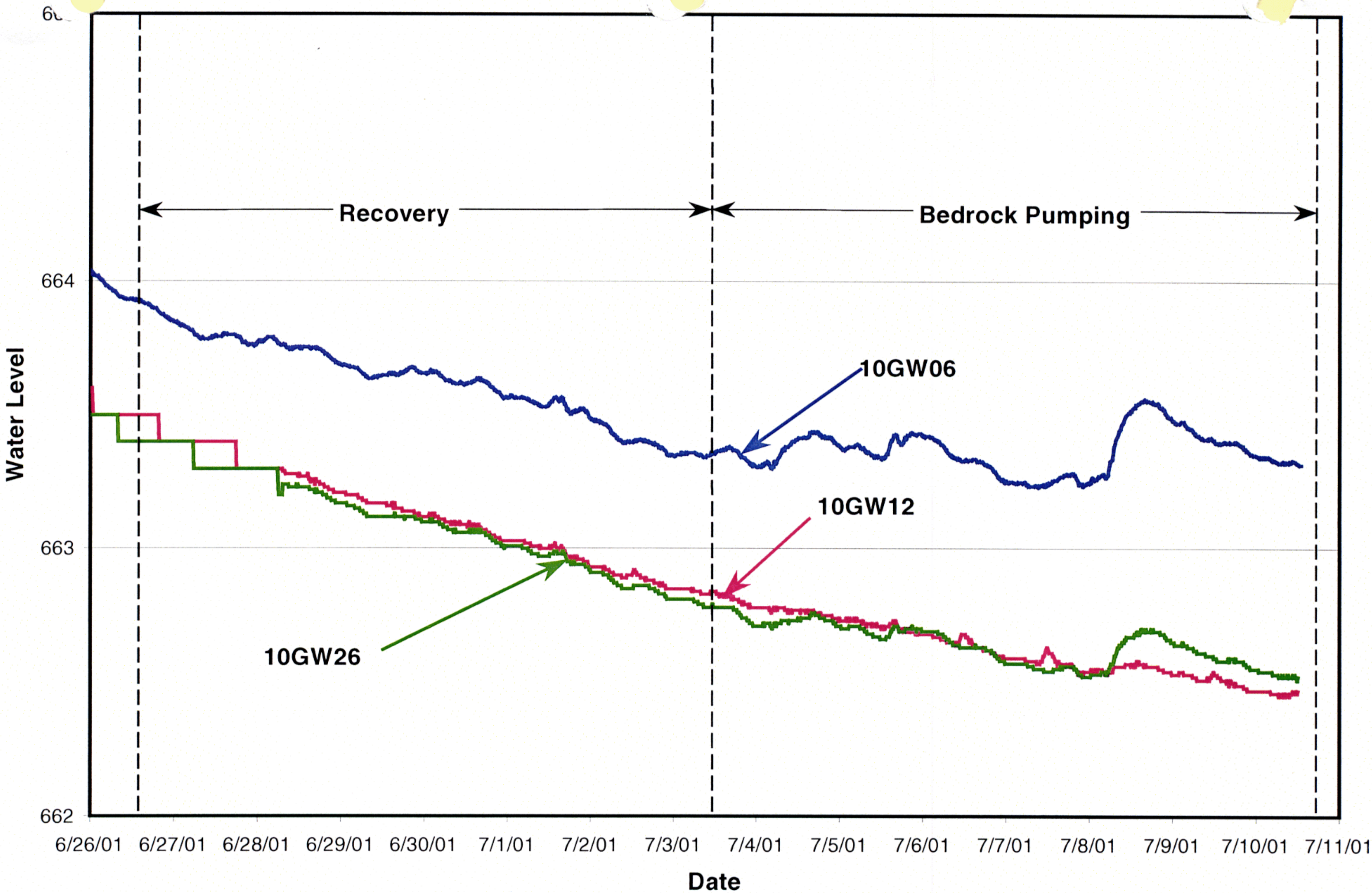

Figure D-4
Water-Level Records from Data Loggers in Wells 10GW06, 10GW12, and 10GW26
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

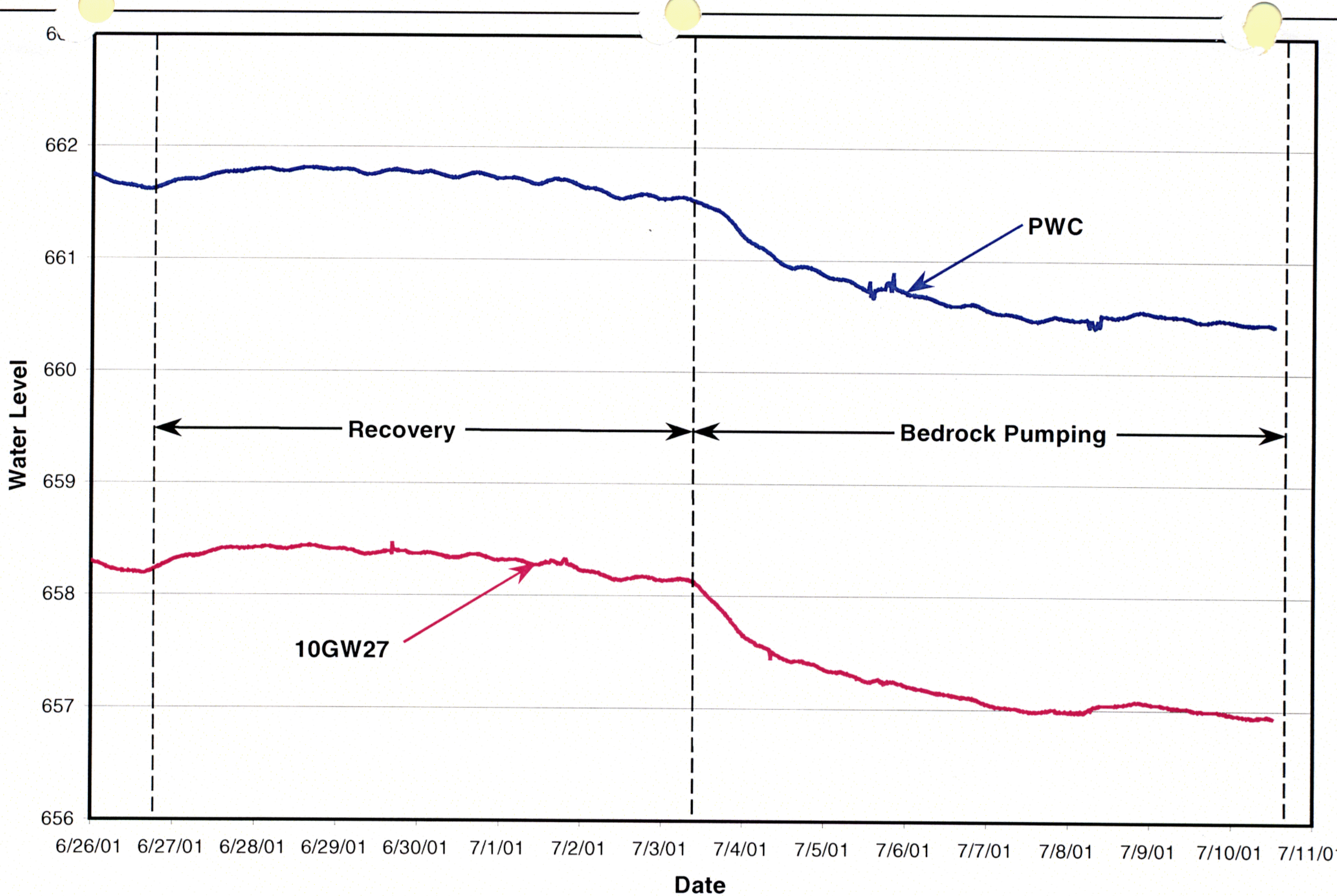

Figure D-5
Water-Level Records from Data Loggers in Wells PWC and 10GW27
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

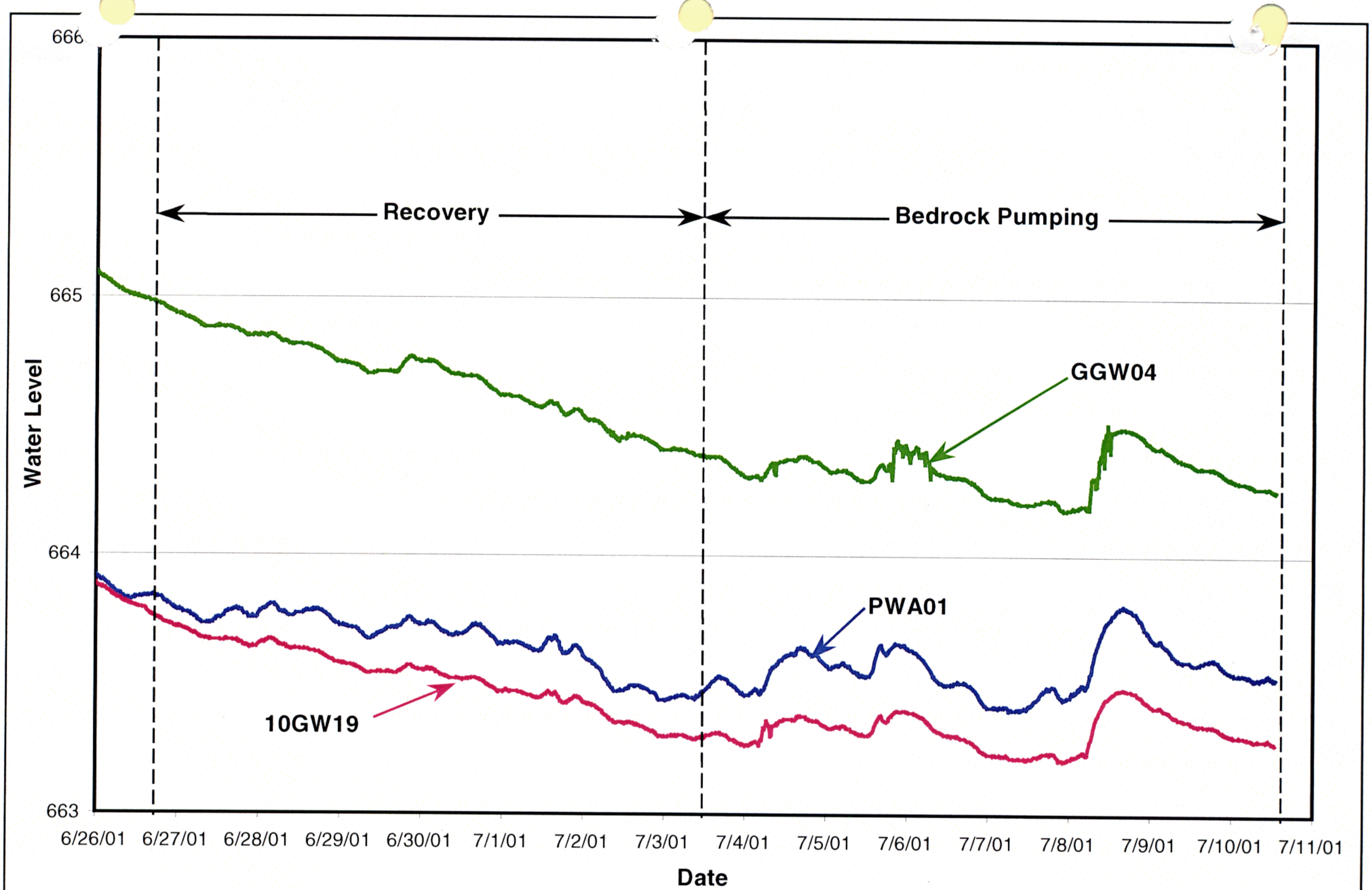

Figure D-6
Water-Level Records from Data Loggers in Wells PWA01, GGW04, and 10GW19
Phase III Aquifer Testing at Site 1 and Site 10
Allegany Ballistics Laboratory

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Appendix E —Revised Site 10 Groundwater Focused Feasibility Study Remedial Alternatives Detailed Cost Estimates

Ta. E-1
Alternative 3
Sitewide Groundwater Extraction and Discharge to the Site 1 Treatment Plant
Cost Estimate Summary

Description	Quantity	Unit	Installed Costs Unit Cost	Installed Costs Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
Capital Expenses								
System Performance Monitoring Wells								
Bedrock Monitoring Well Installation	2	EA	$ 2,750	$ 5,500	$ 1,100	$ 275	$ 825	$ 7,700
Miscellaneous (i.e., IDW)	1	LS	$ 1,750	$ 1,750	$ 350	$ 88	$ 263	$ 2,450
Monitoring Wells Total				$ 7,250	$ 1,450	$ 363	$ 1,088	$ 10,150
Groundwater Extraction System								
Extraction Well Vault Components								
PVC Pipe	5	LS	$ 25	$ 125	$ 25	$ 8	$ 24	$ 181
PE Pump Discharge	250	LF	$ 10	$ 2,500	$ 500	$ 150	$ 475	$ 3,625
Pitless Adapter	10	EA	$ 11	$ 110	$ 22	$ 7	$ 21	$ 160
Recirculation Line	5	EA	$ 15	$ 75	$ 15	$ 5	$ 14	$ 109
Check Valve (V600)	5	EA	$ 40	$ 200	$ 40	$ 12	$ 38	$ 290
Ball Valve (V300)	5	EA	$ 20	$ 100	$ 20	$ 6	$ 19	$ 145
Air Release Valve (V744)	5	EA	$ 55	$ 275	$ 55	$ 17	$ 52	$ 399
Globe Valve (V200)	5	EA	$ 38	$ 190	$ 38	$ 11	$ 36	$ 276
Flexible Hose & Fittings	5	EA	$ 52	$ 260	$ 52	$ 16	$ 49	$ 377
Elbows (8) and Tees (2)	5	LS	$ 48	$ 240	$ 48	$ 14	$ 46	$ 348
Grundfos Redi-Flo Pump	6	EA	$ 2,000	$ 12,000	$ 2,400	$ 720	$ 2,280	$ 17,400
Magnetometer Flow Meter	5	EA	$ 4,500	$ 22,500	$ 4,500	$ 1,350	$ 4,275	$ 32,625
Electric Actuated Flow Control Valve	5	EA	$ 4,500	$ 22,500	$ 4,500	$ 1,350	$ 4,275	$ 32,625
Pressure Gage	5	EA	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Pressure Transducer	5	EA	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Sample Port	5	EA	$ 50	$ 250	$ 50	$ 15	$ 48	$ 363
1" PVC Schedule 80 Sampling Tube	100	FT	$ 2	$ 200	$ 40	$ 12	$ 38	$ 290
1" PVC Schedule 80 Stilling Tube and Cap	100	FT	$ 3	$ 300	$ 60	$ 18	$ 57	$ 435
Precast Concrete Walls	10	CY	$ 450	$ 4,500	$ 900	$ 270	$ 855	$ 6,525
Excavation	5	LS	$ 2,000	$ 10,000	$ 2,000	$ 600	$ 1,900	$ 14,500
C.I Well Cap	5	EA	$ 200	$ 1,000	$ 200	$ 60	$ 190	$ 1,450
Well Vault Lid	5	LS	$ 2,000	$ 10,000	$ 2,000	$ 600	$ 1,900	$ 14,500
Cut Down Well Casing	5	LS	$ 40	$ 200	$ 40	$ 12	$ 38	$ 290
Piping to Site 1 Treatment Plant								
Excavation to Bedrock	515	CY	$ 16	$ 8,240	$ 1,648	$ 494	$ 1,566	$ 11,948
Pipe Bedding	150	CY	$ 30	$ 4,500	$ 900	$ 270	$ 855	$ 6,525

Table E-1
Alternative 3
Sitewide Groundwater Extraction and Discharge to the Site 1 Treatment Plant
Cost Estimate Summary

Description			Installed Costs		Cont	M/D/I	OH&P	
	Quantity	Unit	Unit Cost	Total	20%	5%	15%	Total
Road/Site Restoration	1	EA	$ 1,800	$ 1,800	$ 360	$ 108	$ 342	$ 2,610
Piping to Tie-In (1.5x4" dbl-wall) and leak detection sumps	1300	LF	$ 6	$ 7,800	$ 1,560	$ 468	$ 1,482	$ 11,310
Frame & Cover	5	EA	$ 210	$ 1,050	$ 210	$ 63	$ 200	$ 1,523
Electrical								
Wiring (1000'), Flow Indicator and Switches	5	LS	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Motor Starter SS	5	LS	$ 1,000	$ 5,000	$ 1,000	$ 300	$ 950	$ 7,250
Breaker Panel Switch on Existing Panel	5	LS	$ 100	$ 500	$ 100	$ 30	$ 95	$ 725
I/O Module	5	LS	$ 500	$ 2,500	$ 500	$ 150	$ 475	$ 3,625
New Utility Trenches	1120	LF	$ 3	$ 3,360	$ 672	$ 202	$ 638	$ 4,872
Excavation and Backfill	195	CY	$ 16	$ 3,120	$ 624	$ 187	$ 593	$ 4,524
Concrete Encased RGS	110	CY	$ 100	$ 11,000	$ 2,200	$ 660	$ 2,090	$ 15,950
Tie-In to Existing Electrical Vault	5	LS	$ 400	$ 2,000	$ 400	$ 120	$ 380	$ 2,900
Road/Site Restoration	1	LS	$ 1,800	$ 1,800	$ 360	$ 108	$ 342	$ 2,610
General Conditions	1	LS	$ 8,500	$ 8,500	$ 1,700	$ 510	$ 1,615	$ 12,325
Extraction System Subtotal				$ 171,195	$ 34,239	$ 10,272	$ 32,527	$ 248,233
Labor Burden	1	LS	$ 45,000	$ 45,000	$ 9,000	$ 2,700	$ 8,550	$ 65,250
Subcontractor Markup	1	LS	$ 23,000	$ 23,000	$ 4,600	$ 1,380	$ 4,370	$ 33,350
Prime Markup on Subcontractor	1	LS	$ 9,000	$ 9,000	$ 1,800	$ 540	$ 1,710	$ 13,050
Extraction System Total				$ 248,195	$ 49,639	$ 14,892	$ 47,157	$ 359,883
Total Capital Expenses								**$ 370,033**
Annual Expenses								
Annual Long-Term Monitoring: Yrs 1-30								
Tri-quarterly Groundwater Sampling	1	LS	$ 30,000	$ 30,000	$ 6,000	$ -	$ 5,700	$ 41,700
Monthly Well Gauging	1	LS	$ 10,000	$ 10,000	$ 2,000	$ -	$ 1,900	$ 13,900
Annual LTM Total: Yrs 1-30								**$ 55,600**
Annual Treatment Plant O&M: Yrs 1-30	1	LS	$ 64,000	$ 64,000	$ 12,800	$ -	$ 12,160	$ 88,960
Annual Treatment Plant O&M Total: Yrs 1-30								**$ 88,960**
Total Annual Expenses								**$ 144,560**

Total Present Worth = $2,900,000

Notes:
Cont = Contingency; M/D/I = Mob/Demob/Insurance; OH&P = Overhead and Profit

Table E-2
Alternative 4
Sitewide Groundwater Extraction, Air Stripping, and Discharge to the Storm Sewer
Cost Estimate Summary

Description	Quantity	Unit	Installed Costs Unit Cost	Installed Costs Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
Capital Expenses								
System Performance Monitoring Wells								
Bedrock Monitoring Well Installation	2	EA	$ 2,750	$ 5,500	$ 1,100	$ 275	$ 825	$ 7,700
Miscellaneous (i.e., IDW)	1	LS	$ 1,750	$ 1,750	$ 350	$ 88	$ 263	$ 2,450
Monitoring Wells Total				$ 7,250	$ 1,450	$ 363	$ 1,088	$ 10,150
Groundwater Extraction System								
Extraction Well Vault Components								
PVC Pipe	5	LS	$ 25	$ 125	$ 25	$ 8	$ 24	$ 181
PE Pump Discharge	250	LF	$ 10	$ 2,500	$ 500	$ 150	$ 475	$ 3,625
Pitless Adapter	10	EA	$ 11	$ 110	$ 22	$ 7	$ 21	$ 160
Recirculation Line	5	EA	$ 15	$ 75	$ 15	$ 5	$ 14	$ 109
Check Valve (V600)	5	EA	$ 40	$ 200	$ 40	$ 12	$ 38	$ 290
Ball Valve (V300)	5	EA	$ 20	$ 100	$ 20	$ 6	$ 19	$ 145
Air Release Valve (V744)	5	EA	$ 55	$ 275	$ 55	$ 17	$ 52	$ 399
Globe Valve (V200)	5	EA	$ 38	$ 190	$ 38	$ 11	$ 36	$ 276
Flexible Hose & Fittings	5	EA	$ 52	$ 260	$ 52	$ 16	$ 49	$ 377
Elbows (8) and Tees (2)	5	LS	$ 48	$ 240	$ 48	$ 14	$ 46	$ 348
Grundfos Redi-Flo Pump	6	EA	$ 2,000	$ 12,000	$ 2,400	$ 720	$ 2,280	$ 17,400
Magnetometer Flow Meter	5	EA	$ 4,500	$ 22,500	$ 4,500	$ 1,350	$ 4,275	$ 32,625
Electric Actuated Flow Control Valve	5	EA	$ 4,500	$ 22,500	$ 4,500	$ 1,350	$ 4,275	$ 32,625
Pressure Gage	5	EA	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Pressure Transducer	5	EA	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Sample Port	5	EA	$ 50	$ 250	$ 50	$ 15	$ 48	$ 363
1" PVC Schedule 80 Sampling Tube	100	FT	$ 2	$ 200	$ 40	$ 12	$ 38	$ 290
1" PVC Schedule 80 Stilling Tube and Cap	100	FT	$ 3	$ 300	$ 60	$ 18	$ 57	$ 435
Precast Concrete Walls	10	CY	$ 450	$ 4,500	$ 900	$ 270	$ 855	$ 6,525
Excavation	5	LS	$ 2,000	$ 10,000	$ 2,000	$ 600	$ 1,900	$ 14,500
C.I Well Cap	5	EA	$ 200	$ 1,000	$ 200	$ 60	$ 190	$ 1,450
Well Vault Lid	5	LS	$ 2,000	$ 10,000	$ 2,000	$ 600	$ 1,900	$ 14,500
Cut Down Well Casing	5	LS	$ 40	$ 200	$ 40	$ 12	$ 38	$ 290
Piping to New Treatment Plant								
Excavation to Bedrock	515	CY	$ 16	$ 8,240	$ 1,648	$ 494	$ 1,566	$ 11,948
Pipe Bedding	150	CY	$ 30	$ 4,500	$ 900	$ 270	$ 855	$ 6,525

Table E-2
Alternative 4
Sitewide Groundwater Extraction, Air Stripping, and Discharge to the Storm Sewer
Cost Estimate Summary

Description			Installed Costs		Cont	M/D/I	OH&P	
	Quantity	Unit	Unit Cost	Total	20%	5%	15%	Total
Road/Site Restoration	1	EA	$ 1,800	$ 1,800	$ 360	$ 108	$ 342	$ 2,610
Piping to Tie-In (1.5x4" dbl-wall) and leak detection sumps	1300	LF	$ 6	$ 7,800	$ 1,560	$ 468	$ 1,482	$ 11,310
Frame & Cover	5	EA	$ 210	$ 1,050	$ 210	$ 63	$ 200	$ 1,523
Electrical								
Wiring (1000'), Flow Indicator and Switches	5	LS	$ 1,500	$ 7,500	$ 1,500	$ 450	$ 1,425	$ 10,875
Motor Starter SS	5	LS	$ 1,000	$ 5,000	$ 1,000	$ 300	$ 950	$ 7,250
Breaker Panel Switch on Existing Panel	5	LS	$ 100	$ 500	$ 100	$ 30	$ 95	$ 725
I/O Module	5	LS	$ 500	$ 2,500	$ 500	$ 150	$ 475	$ 3,625
New Utility Trenches	1120	LF	$ 3	$ 3,360	$ 672	$ 202	$ 638	$ 4,872
Excavation and Backfill	195	CY	$ 16	$ 3,120	$ 624	$ 187	$ 593	$ 4,524
Concrete Encased RGS	110	CY	$ 100	$ 11,000	$ 2,200	$ 660	$ 2,090	$ 15,950
Tie-In to Existing Electrical Vault	5	LS	$ 400	$ 2,000	$ 400	$ 120	$ 380	$ 2,900
Road/Site Restoration	1	LS	$ 1,800	$ 1,800	$ 360	$ 108	$ 342	$ 2,610
General Conditions	1	LS	$ 8,500	$ 8,500	$ 1,700	$ 510	$ 1,615	$ 12,325
Extraction System Subtotal				$ 171,195	$ 34,239	$ 10,272	$ 32,527	$ 248,233
Labor Burden	1	LS	$ 45,000	$ 45,000	$ 9,000	$ 2,700	$ 8,550	$ 65,250
Subcontractor Markup	1	LS	$ 23,000	$ 23,000	$ 4,600	$ 1,380	$ 4,370	$ 33,350
Prime Markup on Subcontractor	1	LS	$ 9,000	$ 9,000	$ 1,800	$ 540	$ 1,710	$ 13,050
Extraction System Total				$ 248,195	$ 49,639	$ 14,892	$ 47,157	$ 359,883
Groundwater Treatment System								
Process Equipment and Control								
Sump Pump	1	EA	$ 464	$ 464	$ 93	$ 28	$ 88	$ 672
Transfer Pump (3 hp)	1	EA	$ 2,423	$ 2,423	$ 485	$ 145	$ 460	$ 3,513
Air Stripper (600 scfm blower)	1	EA	$ 25,750	$ 25,750	$ 5,150	$ 1,545	$ 4,893	$ 37,338
Holding Tank (5,000 gal fiberglass)	1	EA	$ 9,074	$ 9,074	$ 1,815	$ 544	$ 1,724	$ 13,158
Back-presr valves/pulsation dampers/presr release valves	1	SET	$ 6,695	$ 6,695	$ 1,339	$ 402	$ 1,272	$ 9,708
Magnetometer	1	EA	$ 5,675	$ 5,675	$ 1,135	$ 341	$ 1,078	$ 8,229
Autodialer w/remote monitoring	1	EA	$ 3,435	$ 3,435	$ 687	$ 206	$ 653	$ 4,981
Control Panel	1	EA	$ 9,857	$ 9,857	$ 1,971	$ 591	$ 1,873	$ 14,293
Motor control center (MCC)	1	EA	$ 41,818	$ 41,818	$ 8,364	$ 2,509	$ 7,945	$ 60,636
Storm Sewer Extension								
Manhole	2	EA	$ 1,236	$ 2,472	$ 494	$ 148	$ 470	$ 3,584
Concrete pipe (12")	160	LF	$ 9	$ 1,418	$ 284	$ 85	$ 269	$ 2,056

Table E-2
Alternative 4
Sitewide Groundwater Extraction, Air Stripping, and Discharge to the Storm Sewer
Cost Estimate Summary

Description	Quantity	Unit	Installed Costs Unit Cost	Installed Costs Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
Building (22'x32')								
Structure	704	SF	$ 46	$ 32,630	$ 6,526	$ 1,958	$ 6,200	$ 47,314
Heating/ventilation	704	SF	$ 12	$ 8,701	$ 1,740	$ 522	$ 1,653	$ 12,617
Concrete Slab								
Slab Concrete	51	CY	$ 196	$ 9,981	$ 1,996	$ 599	$ 1,896	$ 14,472
Granular Fill	35	CY	$ 31	$ 1,082	$ 216	$ 65	$ 205	$ 1,568
Excavation	156	CY	$ 10	$ 1,607	$ 321	$ 96	$ 305	$ 2,330
Backfill/compaction	105	CY	$ 22	$ 2,271	$ 454	$ 136	$ 432	$ 3,293
Treatment Plant Subtotal				$ 165,352	$ 33,070	$ 9,921	$ 31,417	$ 239,761
Miscellaneous Metals	2%			$ 6,484	$ 1,297	$ 389	$ 1,226	$ 9,396
Finishes	2%			$ 6,484	$ 1,297	$ 389	$ 1,226	$ 9,396
Sitework	5%			$ 16,211	$ 3,242	$ 973	$ 3,064	$ 23,490
Miscellaneous Structural	3%			$ 9,727	$ 1,945	$ 584	$ 1,838	$ 14,094
Miscellaneous Mechanical	12%			$ 38,906	$ 7,781	$ 2,334	$ 7,353	$ 56,374
Electrical/I&C	25%			$ 81,055	$ 16,211	$ 4,863	$ 15,319	$ 117,448
Treatment Plant Total				$ 324,219	$ 64,843	$ 19,453	$ 61,443	$ 469,959
Total Capital Expenses								**$ 839,992**
Annual Expenses								
Annual Long-Term Monitoring: Yrs 1-30								
Tri-quarterly Groundwater Sampling	1	LS	$ 30,000	$ 30,000	$ 6,000	$ -	$ 5,700	$ 41,700
Monthly Well Gauging	1	LS	$ 10,000	$ 10,000	$ 2,000	$ -	$ 1,900	$ 13,900
Annual LTM Total: Yrs 1-30								**$ 55,600**
Annual Treatment Plant O&M: Yrs 1-30	1	LS	$ 145,000	$ 145,000	$ 29,000	$ -	$ 27,550	$ 201,550
Annual Treatment Plant O&M Total: Yrs 1-30								**$ 201,550**
Total Annual Expenses								**$ 257,150**

Total Present Worth = $5,300,000

Notes:
Cont = Contingency; M/D/I = Mob/Demob/Insurance; OH&P = Overhead and Profit

T... E-3
Alternative 8
Focused Groundwater Extraction, Air Stripping, and Discharge to the Storm Sewer
Cost Estimate Summary

Description	Quantity	Unit	Unit Cost	Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
	Installed Costs							
Capital Expenses								
Groundwater Treatment System								
Process Equipment and Control								
Sump Pump	1	EA	$ 464	$ 464	$ 93	$ 28	$ 88	$ 672
Transfer Pump (1.5 hp)	1	EA	$ 1,864	$ 1,864	$ 373	$ 112	$ 354	$ 2,703
Air Stripper (300 scfm blower)	1	EA	$ 23,072	$ 23,072	$ 4,614	$ 1,384	$ 4,384	$ 33,454
Holding Tank (2,000 gal fiberglass), back pressure	1	EA	$ 5,923	$ 5,923	$ 1,185	$ 355	$ 1,125	$ 8,588
Back-presr valves/pulsation dampers/presr release valves	1	SET	$ 5,768	$ 5,768	$ 1,154	$ 346	$ 1,096	$ 8,364
Magnetometer	1	EA	$ 5,675	$ 5,675	$ 1,135	$ 341	$ 1,078	$ 8,229
Autodialer w/remote monitoring	1	EA	$ 3,435	$ 3,435	$ 687	$ 206	$ 653	$ 4,981
Control Panel	1	EA	$ 6,571	$ 6,571	$ 1,314	$ 394	$ 1,249	$ 9,529
Motor control center (MCC)	1	EA	$ 32,445	$ 32,445	$ 6,489	$ 1,947	$ 6,165	$ 47,045
Storm Sewer Extension								
Manhole	2	EA	$ 1,236	$ 2,472	$ 494	$ 148	$ 470	$ 3,584
Concrete pipe (12")	160	LF	$ 9	$ 1,418	$ 284	$ 85	$ 269	$ 2,056
Building (16'x24')								
Structure	384	SF	$ 46	$ 17,798	$ 3,560	$ 1,068	$ 3,382	$ 25,808
Heating/ventilation	384	SF	$ 12	$ 4,746	$ 949	$ 285	$ 902	$ 6,882
Concrete Slab								
Slab Concrete	28	CY	$ 196	$ 5,480	$ 1,096	$ 329	$ 1,041	$ 7,945
Granular Fill	19	CY	$ 31	$ 587	$ 117	$ 35	$ 112	$ 851
Excavation	86	CY	$ 10	$ 886	$ 177	$ 53	$ 168	$ 1,284
Backfill/compaction	58	CY	$ 22	$ 1,255	$ 251	$ 75	$ 238	$ 1,819
Treatment Plant Subtotal				$ 119,858	$ 23,972	$ 7,191	$ 22,773	$ 173,795
Miscellaneous Metals	2%			$ 4,700	$ 940	$ 282	$ 888	$ 6,810
Finishes	2%			$ 4,700	$ 940	$ 282	$ 888	$ 6,810
Sitework	5%			$ 11,751	$ 2,350	$ 705	$ 2,221	$ 17,027
Miscellaneous Structural	3%			$ 7,050	$ 1,410	$ 423	$ 1,333	$ 10,216
Miscellaneous Mechanical	12%			$ 28,202	$ 5,640	$ 1,692	$ 5,330	$ 40,864
Electrical/I&C	25%			$ 58,754	$ 11,751	$ 3,525	$ 11,104	$ 85,134
Treatment Plant Total				$ 235,015	$ 47,003	$ 14,100	$ 44,537	$ 340,656
Total Capital Expenses								$ 340,656

Ta... E-3
Alternative 8
Focused Groundwater Extraction, Air Stripping, and Discharge to the Storm Sewer
Cost Estimate Summary

Description	Installed Costs Quantity	Unit	Unit Cost	Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
Annual Expenses								
Annual Long-Term Monitoring: Yrs 1-30								
Tri-quarterly Groundwater Sampling	1	LS	$ 30,000	$ 30,000	$ 6,000	$ -	$ 5,700	$ 41,700
Monthly Well Gauging	1	LS	$ 10,000	$ 10,000	$ 2,000	$ -	$ 1,900	$ 13,900
Annual LTM Total: Yrs 1-30								**$ 55,600**
Annual Treatment Plant O&M: Yrs 1-30	1	LS	$ 54,000	$ 54,000	$ 10,800	$ -	$ 10,260	$ 75,060
Annual Treatment Plant O&M Total: Yrs 1-30								**$ 75,060**
Total Annual Expenses								**$ 130,660**

Total Present Worth = $2,600,000

Notes:
Cont = Contingency; M/D/I = Mob/Demob/Insurance; OH&P = Overhead and Profit

Table E-4
Alternative 9
Focused Groundwater Extraction and Discharge to the Site 1 Treatment Plant
Cost Estimate Summary

Description	Quantity	Unit	Installed Costs Unit Cost	Installed Costs Total	Cont 20%	M/D/I 5%	OH&P 15%	Total
Total Capital Expenses								$ -
Annual Expenses								
Annual Long-Term Monitoring: Yrs 1-30								
Tri-quarterly Groundwater Sampling	1	LS	$ 30,000	$ 30,000	$ 6,000	$ -	$ 5,700	$ 41,700
Monthly Well Gauging	1	LS	$ 10,000	$ 10,000	$ 2,000	$ -	$ 1,900	$ 13,900
Annual LTM Total: Yrs 1-30								**$ 55,600**
Annual Treatment Plant O&M: Yrs 1-30	1	LS	$ 54,000	$ 54,000	$ 10,800	$ -	$ 10,260	$ 75,060
Annual Treatment Plant O&M Total: Yrs 1-30								**$ 75,060**
Total Annual Expenses								**$ 130,660**

Total Present Worth = $2,300,000

Notes:
Cont = Contingency; M/D/I = Mob/Demob/Insurance; OH&P = Overhead and Profit